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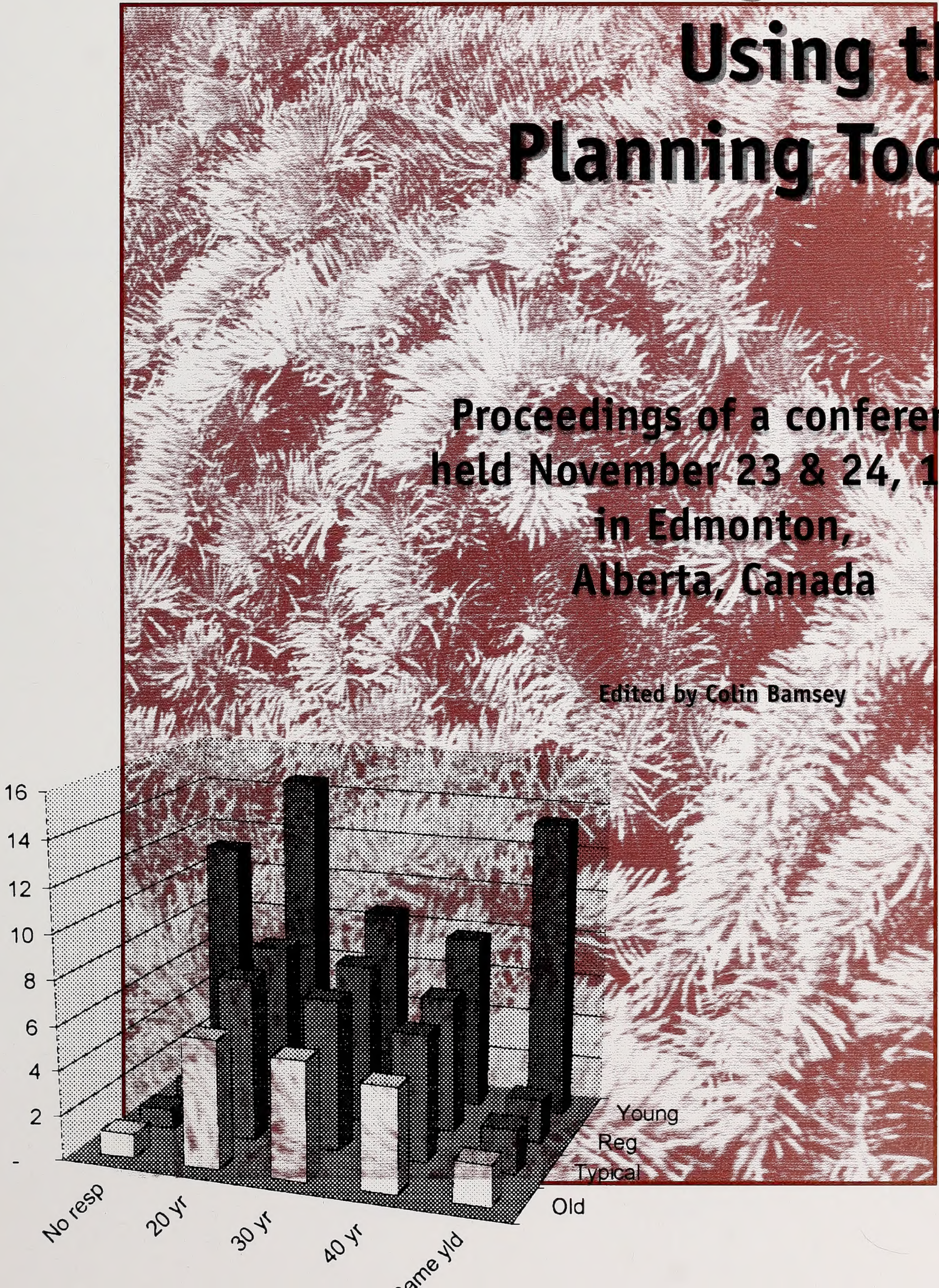
Stand Density Management: Using the Planning Tools



Proceedings of a conference held November 23 & 24, 1998 in Edmonton, Alberta, Canada

Edited by Colin Bamsey

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Proceedings:

Stand Density Management: Using the Planning Tools

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edited by Colin R. Bamsey, RPF

Alberta
ENVIRONMENTAL
PROTECTION

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Session moderators helped focus each of the presentations, and added their individual knowledge to the conference. They were:

- Dave Morgan, Environmental Protection, Resource Information Centre
- Richard Krygier, Millar Western Industries Ltd.

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Front and back cover photos: Colin Bamsey.
Stand Density Management Diagram: Willi Fast and Ted Gooding

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PREFACE

Alberta's resource managers are continually seeking appropriate planning tools for multi-resource and mixed species applications. As a follow-up to Stand Density Managment: Planning and Implementation, a 1997 conference that dealt with the full range of issues and opportunities surrounding crop planning and stand density management, this 1998 conference provided a more detailed look at the models in use today.

Which is the best model? The answer is "it depends," and once you've read the papers that follow, you'll know the pros and cons and be able to decide for yourself where each model or method is or is not applicable.

Mixedwood Growth Model — MGM — Potential for Stand Density Management

S.J. Titus[1]

The Mixedwood Growth Model (MGM) is a tree-based stand growth simulator. It uses major boreal tree species (Sw, Aw, Pl, Sb) growing in pure or mixed stands.

Growth and yield issues in the boreal forest that have been identified are:

1. there are many species including deciduous and coniferous
2. there are many ages
3. there are many changes in composition over time
4. it is difficult to measure sites
5. there is little data for young stands
6. in some regions, there is little data for any stands
7. we have a need for yield estimates now

The goal of the model is to simulate growth and yield for typical stands of mixed species composition in Alberta. The approach is similar to the Prognosis model in that it is an individual tree (not a whole stand) model and it is an aspacial (not a spatial) model. It utilizes typical forest inventory characteristics and it incorporates existing relationships.

Capabilities of MGM

Potential capabilities of tree-based models include that mixed species composition and succession can be included. It also looks at the tree height, diameter, form, and volume. The model has the potential to use the distribution of trees by size and to create a simulation of treatments.

Uniform and regular distribution may or may not work in these kinds of models. It can potentially include multi-layer or multi-age or uneven-aged conditions in the stand. This is because the nature of the model deals with a typical list of trees that will reflect the stand therefore these kinds of conditions can at least potentially be included.

Stand conditions can also be summarized as yield tables presented in a fairly typical format. Lastly, although some models don't deal with this currently, there is potential to look indirectly at some of the biodiversity issues from the other values issues that fall on other characteristics of interest.

Stand dynamics

To look more directly at the MGM model itself it is stand dynamics that we are talking about including establishment of the stand. This can come about from a variety of sources. It could include inventory information such as Phase 3 interpretations or other similar classifications, it could include plot data, real measurements of real trees, or it could include summarized inventory information like stand table data.

Once a stand has been established, the increment of tree diameter, height and form of the tree all need to be incorporated with their basic relations that deal with these. The relationships that we are using are somewhat similar to the relationships that were used in the prognosis model and in addition to that we are attempting to link the height and diameter growth rates so that the tree has an appropriate form.

A tally of trees is portrayed using a logistic function, again similar to the function type that is used in the prognosis model, and the likelihood of individual trees dying on a yearly basis is projected.

The option to provide ingrowth is included. It has been based on some very preliminary data on a very small data set and it is relatively crude in nature. One of the approaches, which is somewhat unrealistic in terms of the way we would like to do things, but based on available data, trees larger than 1.9 cm can be approximated as new growth trees. This was based on the Alberta Forest Service permanent sample plot (PSP) data that has a limitation for that size of tree. This is a relatively crude component. It is provided as an option but it is often ignored.

Regeneration and early growth of juvenile stands are also included in the model. This allows for the stand to be harvested either from a partial cutting perspective or a clearcutting perspective and be followed by the re-establishment of a new stand.

MGM components

To look at the simulator itself, basically there is the model that includes the basic relationships that I just went over.

---

[1] Dept. of Renewable Resources, University of Alberta

There is a stand that we are to project and that stand is operated upon by the model, a new stand is projected on a yearly basis and that process is repeated sequentially until there is a desire to have a report on what the stand will look like. Periodic stand summaries are prepared. The simulation software is composed of two main MGM components. One is a growth simulation engine, which is the actual set of mathematical relationships in models that are used to project the trees. The second is an interface that provides the user the ability to operate the model based on a friendly Microsoft Excel spreadsheet interface that accesses the simulation engine.

The MGM stand model is relatively straightforward and simple. There is a name or an identifier associated with the model. There is an age vector that includes information about age, the current year, and the calendar year of origin. A site vector provides site index information about the species of interest. The four primary species of interest are white spruce (Sw), lodgepole pine (Pl), aspen (Aw), and black spruce (Sb).

The tree list includes species, diameter, expansion per hectare factor (TRF), height, total age, and breast height age. The tree list can be based on real data, which is measurement data. It can be simulated based on normal DBH distribution of cohorts and there can be more than one cohort. The trees can also be simulated from the juvenile perspective although the ability to do that is somewhat limited by the data and that the stand is essentially only allowed to start at eight years of age. Treatments may be included in the crop plan.

Crop planning

The MGM Crop Plan is used as a representation of the sequence of events during the life of a stand. An example of a crop plan could include options settings for things such as merchantability; site index and region of the application; establishment of that stand in terms of where the data is coming from; what the site index values are, etc.; growth of the stand for any number of periods of time. Events could include thinning, harvest, and/or regeneration to identify partial cutting, final cutting and perhaps the establishment of new trees within the stand.

The MGM stand summary report includes:

1. Age at time of report.
2. Coniferous/deciduous species breakdown, including:
   - density/ha.
   - average diameter.
   - average height.
   - basal area/ha.
   - total or merchantable volume/ha.
3. Graphs and yield tables.

Figure 1 shows the year of the stand development and the volume per hectare on the y-axis. By projecting the deciduous component of the stand and the coniferous component of the stand, you can see that at about 140 years after the aspen is declining, the spruce is taking over and dominating the stand.

Validation

In terms of MGM validation we've taken two approaches to this point. The first study was from Alberta and it used a sub-sample of data that we used to develop the model. All of the relationships in the model have been developed from Alberta data. The largest component of that data is the PSP. When we did a validation study we selected 100 random PSPs within Alberta for comparisons of 5- to 15-year short term projections with PSP measurements.

So the beginning point of the time frame was the actual PSP measurement, which was the starting point of the growth model. The ending point objective was based on the 5- to 15-year re-measurement time for the PSP. Those two values were then compared to see how the model performed. We did this for five species composition groups, Pl, Sw, and Aw—predominantly pure at 80% composition—as well as a deciduous and a coniferous group, which were 51-80% with other species included. The basic comparison was with total gross volume as well as some other characteristics.

The x-axis in Figure 2 is the actual measurement from the PSP; the model projection of the height is on the y-axis. For this particular graph it is an average of all the trees. You can see that there is a reasonably good correspondence of the height pattern for the overall plot summarization for the model compared to the real data. No particular trends emerge from this example.

Figure 3 shows quadratic average diameter. There is a slight tendency to be under as the stand diameter gets to be quite large. In the younger ages, having 5-30 cm diameter, it is looking reasonable.

Figure 4 shows density. There are a couple of unusual values in terms of density after the end of the growth measurement period particularly at the actual density of 1500 there is a pine that is looking a little bit out of line so that may be an unusual mortality situation. The relative trend is pretty close to actual.

Looking at volume, things are more variable. There is quite a bit more variation. There may be a trend going into the deciduous and this example is a little under the line. Again the overall trend is not that unusual.

We also did some comparisons within British Columbia (BC). MGM Projections were plotted with Northeastern BC temporary and permanent plot database for that region of BC included plots that were predominantly Aw and Sw. We also did twelve projection comparisons of three different site classes and four different species mixes. The example I have included here is for a mixed aspen/spruce stand on good site (20 for aspen, 20 for spruce). All of these comparisons were based on previously compiled data from BC so there are some site differences in the variables. We tried to approximate the merchantable volumes as closely as we could. The height comparison was slightly different.

The data set in Figure 5 shows a reasonable comparison of the total volume of the stand. This is on a good site. There was a minimum diameter of 7.5cm. This is based on a large set of data that was selected to improve the site index that we were interested in but there is still quite a bit of variation. With regard to the BC data set, this data was not used in model development, simply for validation.

Figure 6 shows age versus volume.

As a result of this conference, we attempted to do some things with stand density management. It wasn't something we had set the model up to do in the first place so we were doing things for the first time. I tried to work within the context of what I had available from the model in terms of the orientation, the interface and the relationships. I have ended up with results that don't look like the stand density management diagrams that are seen with various other presentations.

The graphs presented do not use the log scale as is typical to most stand density management diagrams. The initial stand age for this example and simulations is 20 years. I did four initial densities which I picked relatively quickly and somewhat arbitrarily, therefore I don't know that the numerical results coming out of this example would necessarily be realistic from a silvicultural operations perspective. At any rate they illustrate the potential.

I used four initial densities—2400, 1800, 1200, and 600. In these runs I am only showing the spruce component of the stand for the comparisons. but there was an aspen component, which was about 2500 trees per hectare—equal to the highest level density of the spruce. I used the same site index for all runs. The last comment was more for my own information than for background. We have some height adjustments going on inside the model. We didn't use those default height adjustments in order to accentuate the results that you might see in terms of the differences from other characteristics.

Density management charts

In the first example (Figure 7), on the x-axis is the density of the stand with the initial density being at the bottom and to the right and the current density going up and to the left. This is somewhat similar to the stand density management diagrams that I looked at and was trying to duplicate. But in the time that I was trying to do that and with the tools that were readily available within Excel, I wasn't able to do that. I portrayed age of the stand versus density of the stand and we could take a density from the 2400 trajectory and move it back to the left to the second from left trajectory and allow the stand to grow and see what happens.

On all of the graphs in Figure 8, the x-axis is density. On the upper left graph, the y-axis is volume per tree—which is the typical y-axis on the stand density management diagram. The upper right graph shows on the y-axis the height of the trees and therefore projects what will happen with the height. The lower left graph has the total volume of the stands on a per hectare basis displayed on the y-axis and shows that, in this case, with increasing density there is increasing volume. This is in contrast to volume per tree (VPT), which increases with lower density. The last graph shows the mean density versus average diameter, and the average diameter of the tree at the end of the trajectory is larger with the lower initial density.

The information that is portrayed here isn't organized in the same way but the content is the same as what is typically seen in the stand density management diagrams. With the time frame that I had and the tools that I was constraining myself to use, I couldn't make that diagram. I think the information is here and the only constraint is that the model isn't set up to portray this set of graphs. From this I put together some simple crop plans that would illustrate what would happen.

In Table 1 we are looking at starting the stand from 2400 trees per hectare, growing it until age 160 years. At that time there would be 680 trees (coniferous; the aspen were left alone). The mean tree volume would be .67 m^3, the height of the trees would be about 26 meters and the diameter 28 cm with a total volume of 460 m^3. This is with no treatments.

Table 2 shows the same initial density (2400 trees/ha) at age 20 growing to age 80. At that time the density could be brought down to the same value as the point portrayed in the tables (about 1800 trees/ha). The final density was 691 trees and 88 m^3. Then growing it to 160 years you have 377 trees with a volume of 347 m^3 and if you add in the thinning volume you will get 385 m^3.

Table 3 shows the same thinning time (initial density 2400 trees/ha) but a more substantial reduction down to the lowest density level that was 356 trees/ha. Then it is grown to 160 years where there is 199 trees/ha and you have 227 m³. The thinning produces 72 m³ which equals 299 m³ when totaled.

Comparison of crop plans

In Table 4, you can see that the tradeoffs between MTV (DBH) and volume that would be possible. The heights of trees are relatively unaffected by density. There is no financial data but an economic analysis could be completed using Excel tools. This may not be a "good" set of alternatives in terms of doing this kind of treatment.

Why this approach? My first interpretation is that Excel doesn't do SDM Diagrams. There is the option for you to make a direct linkage to growth model simulations. I did four simulations. Also runs can be made with different species composition and site index. There is less interpolation required and you can read values directly from graphs in Excel. You can simulate the final crop plan as developed from the graphs.

In conclusion the features for the model are that it deals with a friendly and flexible user interface, it has the ability to approximate new scenarios and also the ability to process many crop plans. In terms of development needs, there are things relating to the user interface, there are relationships needing more study, and we also need to look at what other characteristics to portray.

Figures and tables

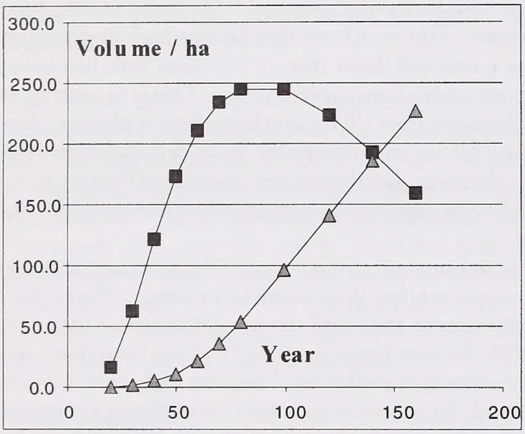

Figure 1: Volume / ha

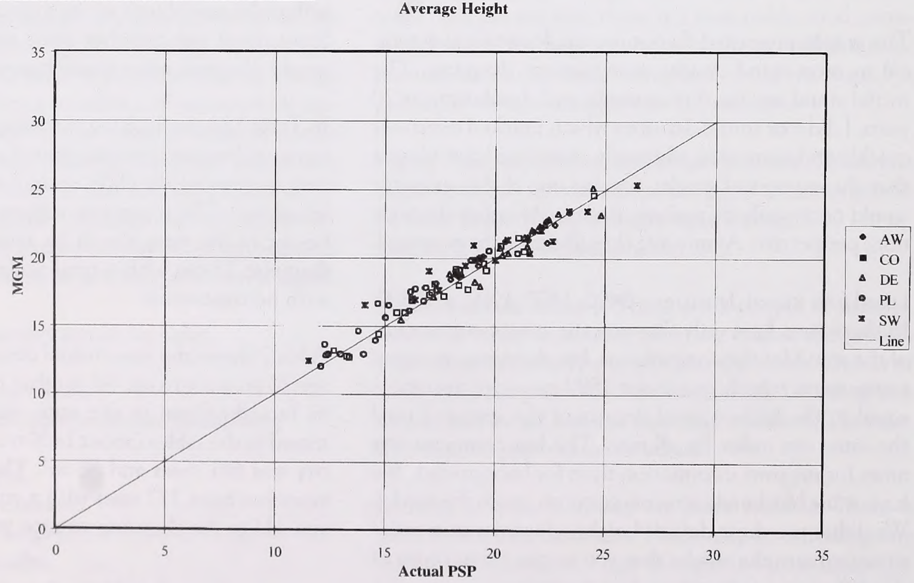

Figure 2: Average Height

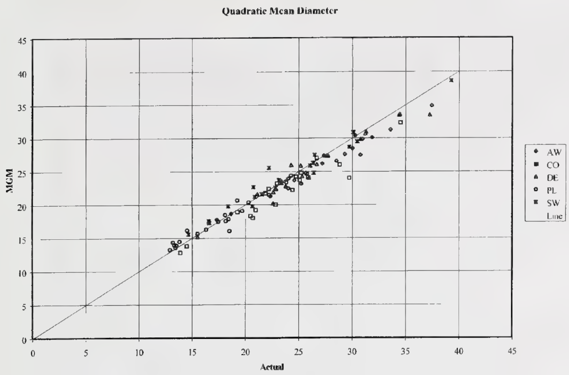

Figure 3: Quadratic Mean Diameter

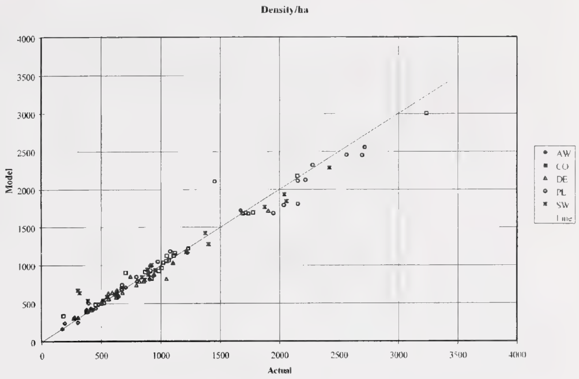

Figure 4: Density / ha

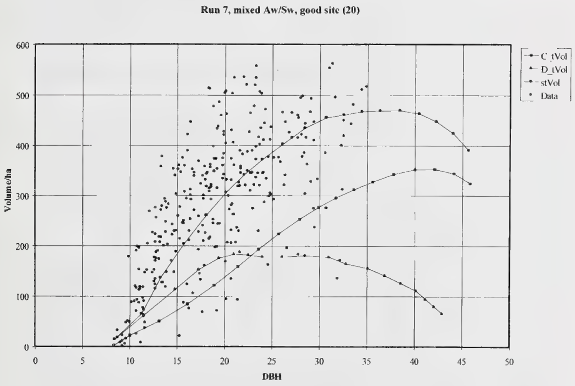

Figure 5: Run 7, mixed Aw/Sw, good site (20)

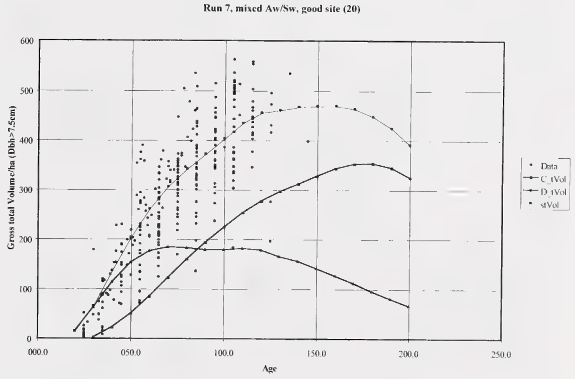

Figure 6: Run 7, mixed Aw/Sw, good site (20)

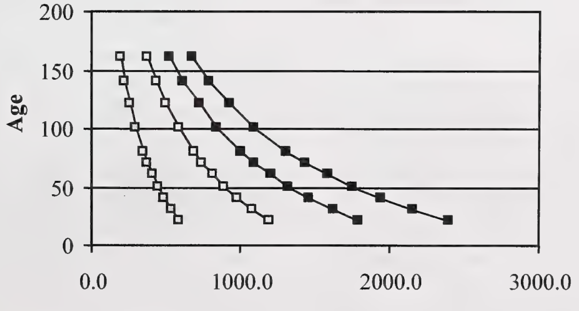

Figure 7: Age trajectories for four initial densities/ha (600, 1200, 1800, 2400)

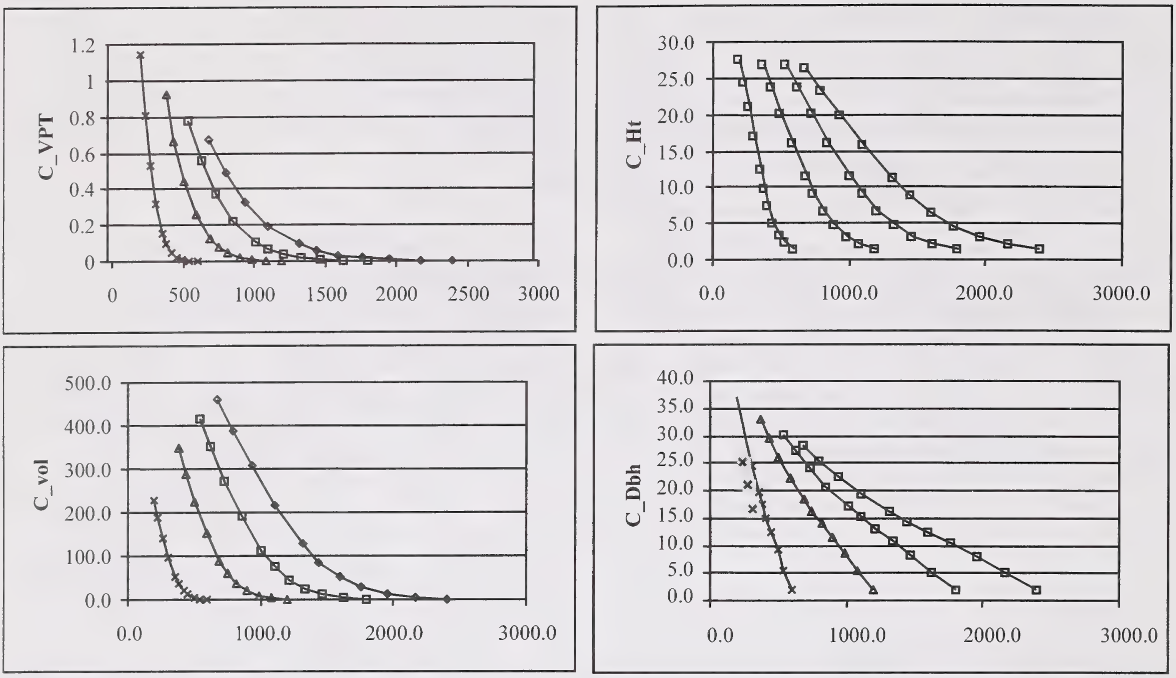

Figure 8: Volume per tree (VPT), conifer average height (C_Ht), volume per ha (C_vol), and average diameter (C_Dbh) trajectories for four initial dnesities/ha (600, 1200, 1800, 2400)

Crop Plan 1 (natural)

AGE	TPH	MTV	HT	DBH	VOL
20	2400	—	—	—	—
160	680	0.676	26.3	28.3	460

Table 1: Crop Plan 1 (natural)

Crop Plan 2 (medium thinning)

	TPH	MTV	HT	DBH	VOL
20	2400	—	—	—	—
80	1318	0.096	11.2	16.2	125
—	(thin)	—	—	—	(38)
80	691	0.127	11.6	18.3	88
160	377	0.920	26.8	33.1	347
—	—	—	—	—	385

Table 2: Crop Plan 2 (medium thinning)

Crop Plan 3 (heavy thinning)

AGE	TPH	MTV	HT	DBH	VOL
20	2400	—	—	—	—
80	1318	0.096	11.2	16.2	126
—	(thin)	—	—	—	(72)
80	356	—	12.4	19.9	54
160	199	1.139	27.6	37.2	227
—	—	—	—	—	299

Table 3: Crop Plan 3 (heavy thinning)

Plan	TPH	MTV	HT	DBH	VOL
1	680	0.676	26.3	28.3	460
2	377	0.920	26.8	33.1	385
3	199	1.139	27.6	37.2	299

Table 4: Comparison of Crop Plans

TASS/SYLVER/TIPSY:
Systems for predicting the impact of silvicultural practices on yield, lumber value, economic return and other benefits

C. Mario Di Lucca[1]

Abstract

Stand density management has become a very important issue in British Columbia and Alberta from the point of view of timber production and its implications on economics and forest level analysis. This paper describes three systems designed to assess the affects of density management on stand yield, product recovery and quality, and financial return. Forest managers responsible for stand density decision-making can use these systems to prescribe stand-specific treatments in support of production objectives.

Introduction

This paper describes the main components and information which support three growth and yield systems used in British Columbia to predict potential yields of even-aged coniferous stands of commercial importance. The main difference between these systems is the type and complexity of information they require and produce. The Tree And Stand Simulator (TASS) generates growth and yield information for SYLVER and TIPSY. SYLVER evaluates the impact of Silviculture treatments on Yield, Lumber Value and Economic Return. It integrates the yield data from TASS and other sub-systems, and predicts wood quality, product recovery and financial return for various management regimes. Finally, TIPSY (Table Interpolation Program for Stand Yield) electronically accesses managed stand yield and product recovery tables generated by TASS and SYLVER, and performs economic analyses of the silvicultural treatments simulated.

Forest resource managers can use these systems to plan and execute stand density management prescriptions which might include different establishment densities and spatial distributions, and various silvicultural treatments (e.g. pre-commercial thinning and commercial thinning). This information can then be used for silvicultural decision-making, inventory and timber supply analysis.

The Forest Productivity and Decision Support Section (FPDS) of the British Columbia Ministry of Forests Research Branch directs the research, development and support of these systems, with input from other ministry staff and industry. The Province of British Columbia holds the copyright for these systems.

TASS

What is TASS?

TASS is a biologically oriented spatially explicit individual tree model. It was designed to produce potential growth and yield tables for even-aged managed stands. It is calibrated for four coastal and four interior species in British Columbia. TASS is driven by the height growth (i.e. it uses the Ministry recommended site index or height-age curves), branch extension and crown expansion of competing trees. The model grows trees and simulates crown competition in a three-dimensional growing space simulated within a computer. The crowns of individual trees add a shell of foliage each year and either expand or contract asymmetrically in response to internal growth processes, physical restrictions imposed by the crowns of competitors, environmental factors and cultural practices. The volume increment produced by the foliage is distributed over the bole annually, and is accumulated to provide tree and stand statistics. More information about TASS can be found in the publications by Mitchell (1975), Mitchell and Cameron (1985) and Mitchell (1986).

TASS generates the yield table database for TIPSY. It also incorporates a number of sub-models such as ROTSIM (Mitchell and Bloomberg, 1986; Bloomberg, 1990) a laminated root-rot model, SWAT (Alfaro, 1996) a spruce weevil attack model, and TRAYCI (Brunner, 1998) a light interception model. TASS is also the growth and yield component of SYLVER which is described in the next section.

Who developed TASS?

The construction of TASS began in 1963 by Dr. Kenneth J. Mitchell as a research project of the Canadian Forestry Service (Mitchell, 1969) with later support contributed by Yale University (Mitchell, 1975), University of Idaho (Goudie, 1980), British Columbia Ministry of Forests (Mitchell and Cameron, 1985), and other agencies.

---

[1] British Columbia Ministry of Forests, Victoria, British Columbia

What can it do?

TASS generates growth and yield information for even-aged stands of pure coniferous species of commercial importance in coastal and interior forests of British Columbia. It is mainly used for:

- stand level crop planning;
- stand level silvicultural treatment decision-making (e.g. espacement, fertilization, pruning, pre-commercial and commercial thinning);
- forest level planning including long-term timber supply projections for managed second-growth stands;
- pest and disease yield impact predictions (e.g. laminated root rot and spruce weevil);
- predicting height-growth repression in lodgepole pine stands;
- investigations of tree growth and stand dynamics;
- teaching growth and yield, and stand dynamics;
- generating stand density management diagrams; and
- wood quality predictions (i.e. size and distribution of branch knots and juvenile-mature wood distribution) used by SYLVER to determine product value and economic return.

The main limitation of TASS is that it does not predict the yield of complex stands (i.e. mixed-species and/or uneven-aged stands).

What data are behind TASS?

TASS is calibrated to conform with data from research trials and remeasured plots located in managed and unmanaged stands. Most of the biological growth relationships in TASS are derived from detailed stem analysis of tree boles, branches and foliage. A total of 11,989 permanent plots (i.e. comprised of 43,799 plot measurements) established for local species growing within British Columbia, Alberta, the Pacific Northwest region of the United States, Europe and New Zealand have been consistently summarized and classified by species and treatments including control, thinned and fertilized (Goudie, 1998). The number of plots and measurements from untreated natural stands and plantations is listed in Table 1.

FPDS staff test and evaluate TASS on a regular basis using existing and new data. In a recent paper, Jim Goudie (1998) compared model output with plot data from thinned stands to identify potential biases in the predictions. He concluded that the system generally performs very well, but slightly overestimates the response to thinning.

Input options

TASS input parameters are:

- species and stand origin (i.e. single species from natural or planted origin);
- initial number of trees per hectare;
- spatial tree distribution or optional tree map list (e.g. uniform, clump or any possible distribution);
- site index or a combination of height and age;
- volume merchantability limits (e.g. minimum quadratic diameter at breast height outside bark, top diameter inside bark, and stump height);
- operational adjustment factors;
- plot dimensions in meters;
- silvicultural treatments (e.g. pre-commercial and commercial thinning, pruning and fertilization); and
- output table specifications (i.e. height or age range of the simulation and steps).

Coastal			Interior		
Species	**Number of Plots**	**Number of Plot Measurements**	**Species**	**Number of Plots**	**Number of Plot Measurements**
Douglas-fir	885	4539	Lodgepole pine	2160	5351
Western hemlock	1115	4396	White spruce	456	1286
Sitka spruce	173	643	Douglas-fir	348	764
Western red ced	38	163	Western hemloc	5	10
Total	**2211**	**9795**	**Total**	**2969**	**7411**

Table 1. Permanent Sample Plots Description

Output options

Examples of yield tables, sample output images and information produced are presented in the TASS Web site:

http://www.for.gov.bc.ca/research/groups/fpds/tass.htm

Some of these yield tables are described below.

Standard run summary managed stand yield tables including the following variables:

- stand age;
- stand site height;
- stand crown cover percent;
- stand basal area;
- total and merchantable stand volume per hectare;
- total and merchantable stand mean annual volume increment per hectare; and
- average tree statistics (i.e. basal area, top and predominant height, crown area, crown width, crown length, quadratic mean diameter at breast height, total and merchantable height, total and merchantable volume, foliar volume, and total and merchantable gross volume).

Stand tables: display the number of tress or tree count in 5-cm diameter size classes for each stand age requested.

Stock tables: display merchantable volume (0.0+) in 5-cm diameter size classes for each stand age requested.

Mortality tables: display a stand table of the number of trees that die both earlier due to non-competitive juvenile mortality, and later due to suppression between age steps by 5-cm diameter size classes.

Standing dead tree (snag) tables: display a stand table of standing dead trees per hectare by 5-cm diameter size classes. They show the number of dead trees that are still standing at each age step (i.e. a snapshot of standing dead trees).

Customized yield tables: clients may request a variety of yield data for custom spatial distributions, pruning, fertilization, pre-commercial and commercial thinning, root rot and spruce weevil infestation treatments. Response time varies from a day to several weeks depending upon the complexity of the task.

What is in TASS's future?

Current and future developments of TASS include:

- the calibration of TRAYCI, the light interception model;
- a start-up routine to enter data from existing stands;
- a complex stands model for uneven-aged interior Douglas-fir stands in the IDF zone, and for even-aged mixed-species stands in the ICH zone;
- red alder calibration;
- internet on-line access to TASS with the support of the TASS Input Editor program (TASSIE);
- wildlife attributes and environmental indicators (e.g. pileated woodpecker, grizzly bear habitat, cougar, coarse woody debris and "old-growth" dependent values). See publication by Greenough and Kurz (1996);
- a mistletoe model for western hemlock; and
- further model calibration as data become available.

Perhaps one of the most important upgrade relates to the light and moisture components needed to simulate the development of complex stands. Light is necessary to model the variable crown structure found in mixed-species and uneven-aged stands. The dynamics of moisture within a complex stand is uncertain and is currently under investigation.

How to get TASS

TASS is only available in the Research Branch of the Ministry of Forests because it has substantial training and hardware requirements. TASS growth and yield predictions are available in two formats:

- by running the program TIPSY to obtain custom versions of the yield tables generated by TASS for a specific regime; and

- by requesting special TASS runs for yield table options that are not available within TIPSY by contacting Ken Polsson: (250) 387-6948 or E-mail: **Ken.Polsson@gems5.gov.bc.ca**.

In the near future, clients will submit input parameters via TASSIE over the internet. Research Branch staff will complete the run and return the output.
More information about TASS can be found at the TASS Web site at:

http://www.for.gov.bc.ca/research/groups/fpds/tass.htm

and in the publications by Mitchell (1969), Mitchell (1975), Mitchell (1980), Mitchell and Cameron (1985) and Mitchell (1986).

SYLVER

What is SYLVER?

SYLVER is a stand level system that helps forest managers evaluate the impact of Silvicultural treatments on Yield, Lumber Value, and Economic Return. The components and operation of SYLVER are illustrated in Figure 1.

Each element of SYLVER operates independently with information provided by the user or by the preceding elements of the system. The major components are:

- the Tree And Stand Simulator (TASS) that grows the stand and applies silvicultural treatments;
- the Bucking (BUCK) and Sawmill Simulation (SAWSIM) programs that produce logs and lumber from trees grown by TASS;
- the grading routine (GRADE) that classifies the logs and lumber according to quality; and
- the Financial Analysis System (FAN$Y) that determines the discounted net revenue recovered from tending, harvesting and processing the stand.

Who developed SYLVER?

The development of SYLVER started in 1985 as a product of the Douglas-fir Task Force sponsored by Forintek Canada Corporation, Pulp and Paper Research Institute, British Columbia Ministry of Forests, The University of British Columbia, and industry (Kellogg, 1989). The Task Force was divided into 13 projects which studied the basic wood and pulp properties of second-growth stands of coastal Douglas-fir. The last project is the stand level system SYLVER that integrates silviculture and end-product value.

What can it do?

SYLVER predicts wood quality, product value and economic return in full for coastal Douglas-fir, and partially for coastal western hemlock, Sitka spruce, western redcedar, interior Douglas-fir, interior western hemlock, lodgepole pine and white spruce. The main applications of SYLVER are:

- stand level planning;
- silvicultural prescriptions decision-making (e.g. espacement, fertilization, pruning, pre-commercial and commercial thinning);
- forest level planning (e.g. long term timber supply projections from managed stands);
- pest and disease impact prediction (e.g. laminated root rot and spruce weevil);
- tree and stand dynamics, wood quality and economic investigations;
- stand level economics analysis; and
- education and teaching.

Some of the limitations of SYLVER are:

- it can not be distributed as an integrated stand-alone software package;
- it can not predict yield of complex stands (i.e. mixed-species and/or uneven-aged stands); and
- the lumber grade data required to calculate the select structural lumber volume is currently available only for coastal Douglas-fir.

What data are behind SYLVER?

The coastal Douglas-fir version of SYLVER is based on data from six 50-year-old stands representative of managed forests which will be harvested in the future located on Vancouver Island (Kellogg, 1989). The number of trees sampled for each project is outlined below.

- 300 trees were converted to lumber, and evaluated to estimate the log and lumber yield and grade recovery (Middleton and Munro, 1989), kiln drying degrade (Mackay, 1989), strength and stiffness of dimensional lumber (Barrett and Kellogg, 1989), and heartwood treatability (Ruddick, 1989);
- 60 trees to study the relative density distribution (Jozsa et all., 1989), chemical properties (Swan et al., 1989) and longitudinal shrinkage (Nault, 1989);
- 24 trees to study the juvenile-mature wood transition (Di Lucca, 1989);
- 17 trees to study fiber length (Hamm, 1989); and
- 9 trees to study density and chemical properties of juvenile, mature and top wood (Hatton and Hunt, 1989), unbleached Kraft pulp properties (Hatton and Hunt, 1989), and refiner mechanical pulp properties (Hatton and Johal, 1989).

Input options

The input parameters for the SYLVER components shown in Figure 1 are listed below.

TASS input parameters were mentioned in the previous section.

BUCK uses the tree list generated by TASS which contains the information about the tree heights, diameters inside and outside bark for the knotty and juvenile wood

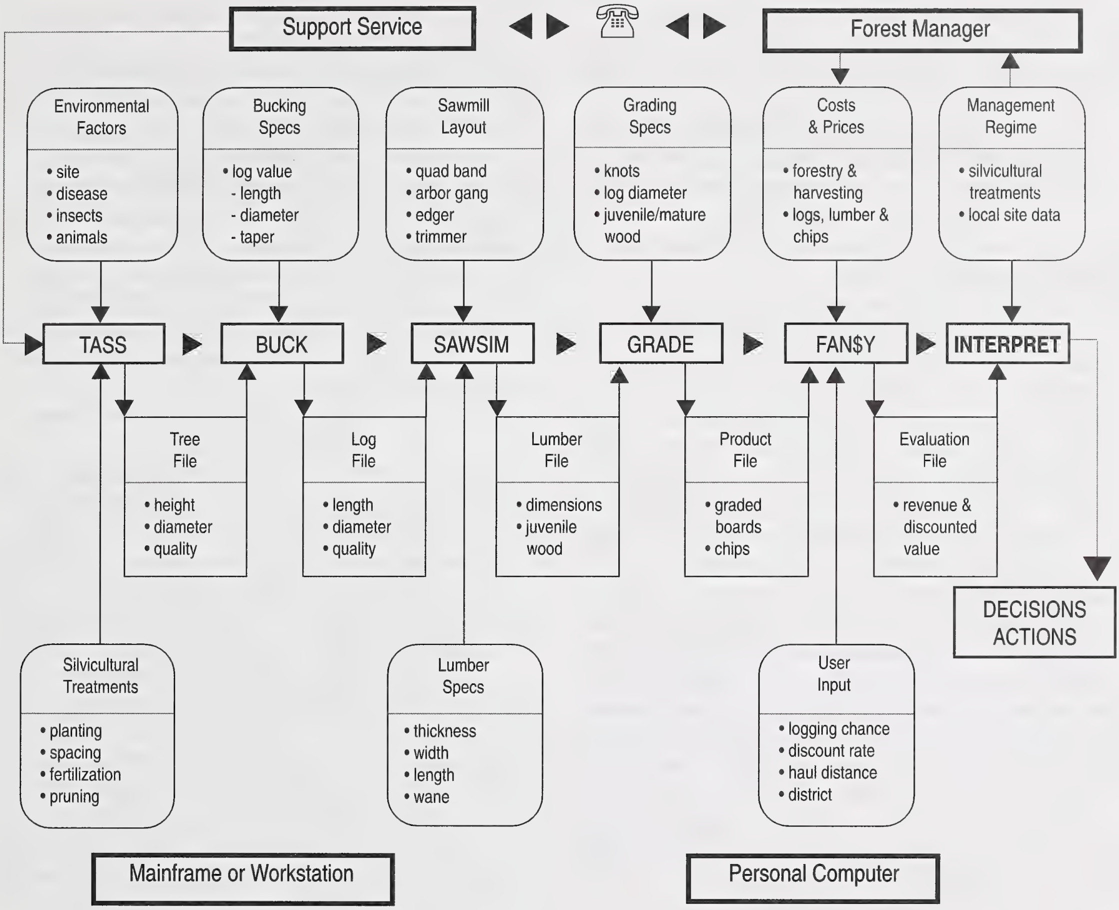

Figure 1: Components and Operation of SYLVER

core, average size and distribution of knots, etc. This program bucks each tree according to specifications (i.e. log length, diameter and taper) that maximize the value of the logs or lumber.

SAWSIM uses the log information generated by BUCK and applies a series of predefined cutting patterns to each log, and selects the one that produces the maximum value based on the determined average market prices. SAWSIM input parameters include the mill configuration (i.e. type of machine and kerf) and lumber specifications (i.e. thickness, width and length). It is a proprietary program developed by Halco Software Systems Ltd.: **http://www.halcosoftware.com**.

GRADE characterizes logs and lumber by quality class. The grading criteria for logs are: minimum length, average small-end diameter, maximum knot diameter and minimum number of annual growth rings per 2 cm. The grading criteria for clear and knotty lumber are: knot content percent, juvenile wood percent, dimensional lumber length, width and thickness.

FAN$Y uses stand, treatment and product information to evaluate the impact of selected silvicultural treatments on the discounted value returned by end products. Some input parameters are:

- land manager (i.e. crown or private); land ownership (i.e. crown or private); and market type (i.e. log or lumber);
- forestry costs (e.g. survey, land rent, brushing and weeding, spacing, fertilization, root rot control, site preparation, planting, pruning, etc.);
- harvesting costs (e.g. infrastructure development, operation and administration overhead, tree-to-truck, hauling, etc.);

- manufacturing costs (e.g. milling, drying, machine stress rating, etc.);
- market prices for logs, lumber and wood chips; and
- financial parameters (e.g. discount rate, U.S. dollar exchange rate, inflation rate, taxes, adjustments factors for future costs and prices, lumber premiums, appraisal data, etc.).

Output options

SYLVER output integrates the yield information, product recovery and financial return from a variety of management regimes. SYLVER is not distributed as an standalone package because TASS, BUCK and SAWSIM must be operated by specialists on a powerful workstation. In contrast, most users have only personal computers and limited training time. To provide access to SYLVER, the Forest Productivity and Decision Support Section divided the operating responsibilities between the user support service and the forest manager as illustrated in Figure 1. Both formulate a series of relevant management regimes and the specifications for bucking, sawing and grading. User support processes all regimes through to the generation of product files, which are forwarded to the forest manager for use with FAN$Y on a personal computer. Then the forest manager can perform sensitivity analyses on the economic specifications to determine the most suitable prescription for local conditions.

To contact the user support call Ken Polsson or Mario Di Lucca at (250) 387-6679 or by E-mail at:

Mario.Dilucca@gems4.gov.bc.ca.

What is in SYLVER's future?

Current and future developments of SYLVER include:

- lodgepole pine and coastal western hemlock;
- an employment generation module;
- the establishment of an expert user group for ongoing testing and development of FAN$Y;
- input options in TASSIE for specifying bucking, sawing and grading parameters.

How to get more information about SYLVER

More information can be found in the SYLVER Web site at:

http://www.for.gov.bc.ca/research/groups/fpds/sylver.htm

and in the publications by Ken Mitchell, et al.(1989 and 1991). SYLVER information is also available via:

- a VHS video entitled "The SYLVER System—Forest Management Simulator" that gives a 10-minute overview of SYLVER. Copies can be borrowed by contacting Shelley Grout at (250) 387-6718 or by E-mail at:

  Shelley.Grout@gems4.gov.bc.ca;
- a computer generated presentation called SYLVER demo (SYLDEMO) that demonstrates the importance of incorporating volume, quality and value criteria into silvicultural decisions. Currently it focuses on the operation of SYLVER to assess wood volume and value, juvenile and mature wood characteristics, and pruning by means of images, animated sequences, and supporting text. A version of this program has been modified for direct viewing at the SYLDEMO Web site at:

  http://www.for.gov.bc.ca/research/groups/fpds/syldemo2.htm; and
- a computer program called Fred's Forest—an interactive forestry management game and training tool designed to demonstrate the capabilities of SYLVER. Players manage a woodlot for profit by selecting the regeneration method, establishment density, thinning and pruning regimes, and harvest age. It displays each treatment, and the subsequent development of the stand, with 3-dimensional graphics, followed by a score (i.e. net discounted profit). Fred's Forest is billed as a game, but its real purpose is to show the public, and kids in particular, that trees really grow and that we can manage them for our benefit. A DOS version of Fred's Forest can be downloaded from the Fred's Forest Web site at:

  http://www.for.gov.bc.ca/research/groups/fpds/fred.htm.

  A new multimedia CD-ROM version 3.1, which operates in both MS Windows and Macintosh environments, is now available on request from Mario Di Lucca.

TIPSY

What is TIPSY?

The Table Interpolation Program for Stand Yield (TIPSY) is not a growth and yield model because it only provides electronic access to the managed stand yield tables generated by TASS and SYLVER. TIPSY retrieves and interpolates yield tables from its database, customizes the information and displays summaries and graphics for a specific site, species and management regime. Information can be entered and displayed in either metric or imperial units. Initial density (i.e. planted or naturally regenerated) and pre-commercial thinning are the primary management variables. It uses optional Operational Adjustment Factors (OAFs) to mimic operational conditions. Two types of OAFs are available in TIPSY to account for elements that reduce potential yields. OAF 1 accounts for the reduction of physical growing space due to holes created by rock outcrops, swamps and non-commercial tree cover. OAF 2 accounts for pest damage that increases towards maturity. A detailed description of OAFs was prepared by Albert Nussbaum (1998). The current version of TIPSY includes an economic analysis module, known as the TIPSY Economist (Stone et al., 1996) which performs economic analyses on the silvicultural treatments simulated by TIPSY. A batch version of TIPSY is also available for processing a large number of stands for timber supply analyses. Batch TIPSY is included in the program WOODLOT (B.C. Ministry of Forests, 1998) for calculating even-flow harvest rates for a planning period on woodlot licenses.

Who developed TIPSY?

The original DOS version or Meta Model was developed by Forests Planning Systems, now part of Reid Collins and Associates. In 1990, RamSoft Systems Ltd. translated the program from BASIC to the C computer language and restructured it to accommodate the next generation of yield tables. The program was renamed to TIPSY and distributed to forest managers across the province along with an user's guide (Mitchell et al., 1992). In 1993 Ramsoft Systems Ltd. rewrote TIPSY to operate in the MS Windows environment and renamed it WinTIPSY. This program was released in January 1996 as Version 1.3 (Mitchell and Grout, 1995). Soon after, the development of the DOS version was discontinued and WinTIPSY became TIPSY again. The current TIPSY Version 2.1 was released in 1998 and is distributed free of charge at the discretion of the Ministry.

What can it do?

TIPSY generates managed stand yield tables, including product recovery data, economic analysis, and supporting graphics for:

- stand level crop planning;
- silvicultural prescriptions (e.g. espacement and pre-commercial thinning);
- forest level planning for long term timber supply projections of managed stands. A multiple species feature aggregates stand types into the timber supply analysis units;
- repressed stands of lodgepole pine;
- dead trees (i.e. standing or fallen);
- investigations of tree growth and stand dynamic;
- generating stand density management diagrams; and
- educational and teaching purposes.

Some of the limitations of the current version of TIPSY:

- it does not predict the yield of complex stands (i.e. mixed-species and/or uneven-aged stands);
- it must initiate stand growth projections at age 0 (i.e. year of disturbance) since data from existing stands cannot be entered. However, establishment parameters can be interactively manipulated to approximate the existing stand conditions at a particular age;
- it allows for only one pre-commercial thinning entry, and it occurs only when stands reach a top height of 4 meters on the interior and 6 meters on the coast.
- it only has two spatial distributions. Planted stands have a nearly uniform square spacing and naturally regenerated stands have a random distribution of seedlings covering the entire site.

What data are behind TIPSY?

TIPSY's database includes 548 managed stand yield tables for: coastal Douglas-fir, coastal western hemlock, Sitka spruce, western redcedar, interior Douglas-fir, interior western hemlock, lodgepole pine and white spruce. TIPSY generates any table within a limited range of parameters provided by the user. If an identical yield table does not exist, TIPSY will interpolate between the closest yield tables and electronically retrieve stand yield information.

Input options

You can enter these parameters in TIPSY:

- species and regeneration method (e.g. natural or planted). An optional multiple species feature will prorate the yields for up to a maximum of 5 species. This option was developed to aggregate stands for the benefit of timber supply planners. It is important to understand that TIPSY does not simulate the growth of multiple species stands biologically. The only biological assumption is the site index conversion among species;
- initial number of trees per hectare;
- operational adjustment factors;
- site index or a combination of height and age;
- silvicultural treatments (e.g. pre-commercial thinning);
- merchantability limits for total volume and merchantable volume;
- the economic analysis will require:
    - * stand geography (i.e. region, district, biogeoclimatic zone and average slope);
    - * discount assumptions (i.e. discount rate, real price and cost increase, real increase duration, base age);

    - silvicultural costs for: surveys, site preparation, planting and pre-commercial thinning;
    - harvesting costs for: different harvesting systems, tree-to-truck, hauling, milling and other miscellaneous costs;
    - product prices for lumber, wood chips and logs; and
    - optional financial and sensitivity analyses.
- output table specifications (height or age range and steps).

Output options

TIPSY generates the following yield tables and information.

Standard managed stand yield tables including:

- total age (i.e. age since disturbance);
- top height;
- gross, total and merchantable volume, and mean annual volume increment per hectare;
- stand basal area;
- quadratic mean diameter at breast height (DBH);
- crown cover percent; and
- for the largest 250 prime or crop trees: merchantable volume, quadratic mean diameter at breast height (DBH) and live crown percent.

Stand tables: display the number of trees by 5-cm diameter size classes for each stand age requested.

Stock tables: take the merchantable volume (12.5 cm+) from the yield table and display it in 5-cm diameter size classes for each stand age requested.

Stand and stock tables combined: display both the number of trees and the merchantable volume in 5-cm diameter size classes for each stand age requested.

Lumber tables: display the board-foot volume of dimensional lumber by 2-inch classes (2x4, 2x6, 2x8, and 2x10), bone dry units of chips, and lumber recovery in board feet per cubic meter.

Log tables: display the total scaled volume (12.5 cm+) of logs which are 2.5 meters (8 ft) or longer in length and its breakdown into standard log market grades.

Economic analysis tables: display the benefit/cost assumptions, net present values, site values and optional financial and sensitivity analyses of a particular management regime.

Mortality tables: display a stand table of the number of trees that die both earlier due to non-competitive juvenile mortality, and later due to suppression between age steps in 10-cm diameter size classes.

Standing dead tree (snag) tables: display a stand table of standing dead trees per hectare in 10-cm diameter size classes. They show the dead trees that are still standing at the age step (i.e. a snapshot of standing dead trees).

What is in TIPSY's future?

Current and future development plans for TIPSY include:

- new treatment options such as: commercial thinning, fertilization, jobs generated and coarse woody debris;
- incorporation of Batch TIPSY into the current interactive version;
- start-up routine to facilitate the entry of data from existing stands;
- incorporation of clumped spatial distributions;
- the ability to create and save customized output table formats.

How to get TIPSY

There are three different ways to get your copy.

- If you work for the Ministry of Forests, check with your systems administrator. All ministry offices should have recently received TIPSY via the Data Delivery System (DDS).
- You can download TIPSY from the Ministry of Forests Growth and Yield Software Registration and Download Web site at:

  http://www.for.gov.bc.ca/cgi-shl/research/gy/softreg.exe

  You can also download the installation instructions and the reference guide for the TIPSY Economist at the same location.
- Finally, if you are unable to get a copy any other way, request a copy on diskettes by contacting Shelley Grout at (250) 387-6718 or E-mail at:

  Shelley.Grout@gems4.gov.bc.ca

  The program comes on three diskettes.

Regardless of how you get your copy of TIPSY, you should register with the Ministry as a user. We will then be able to contact you about upgrades, bugs, and new products. If you download the software from our Web site, you will have the opportunity to register at the same time. If you do not get your copy from the Web site, you should still use our Web site to register without actually downloading.

More information about the TIPSY can be found in the TIPSY Web site at:

http://www.for.gov.bc.ca/research/groups/fpds/tipsy.htm

and in the publication by Mitchell and Grout (1995).

TIPSY comes complete with a comprehensive on-line reference manual which includes a context-sensitive Help system as well as a directory of "experts" who can be contacted regarding the specialized modules such as the TIPSY Economist, snags, or lodgepole pine repression.

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Stand Density Management Diagrams as Growth and Yield Tools For Crop Planning

Craig Farnden, R.P.F.[1]

Stand density management diagrams (SDMDs) are useful for crop planning because they present information in a format which readily illustrates the patterns of change in and interactions between several key descriptive stand parameters. A trained user can readily distinguish, for example, the impact of density changes (trees per hectare) on patterns of stand development, and explore options for density manipulation. Where there are operational options or non-timber values that can be closely associated with the descriptive parameters in the diagrams, these can also be explored. In many cases, these will be dealt with through interpretive overlays (Farnden 1998).

Basic instructions for using stand density management diagrams are available in several publications (Archibald and Bowling 1995, Farnden 1996, Farnden 1998). This article discusses the strengths and weaknesses of SDMDs and presents a crop planning example to illustrate their utility.

Strengths and Weaknesses of SDMDs

While their initial appearance is often intimidating, SDMDs are actually highly simplified models of stand development, growth, and yield. This level of simplification is the root both of the major strengths and the major weaknesses of the diagrams as planning tools. Understanding these strengths and weaknesses is key to effective and appropriate application. A summary of these strengths and weaknesses can be found in Table 1.

Many of the weaknesses of the diagrams can be overcome by using them not in isolation but as a complement to other models. The diagrams developed in British Columbia, for example, are an excellent complement to the TASS model. Where access to TASS is awkward and limited, it is extremely powerful in terms of descriptive parameters and predicting yields for regimes both with and without thinning. It is currently accessible only by making special requests for custom simulations to the B.C. Ministry of Forests Research Branch. Its relative inaccessibility makes it impractical to do a large number of exploratory runs to focus in on desirable density management regimes. Using SDMDs, the silviculturist can quickly and easily get to a close approximation of a regime that will satisfy his/her objectives, followed by just a few runs on the more complex model to provide refinements and additional descriptive parameters.

A Crop Planning Example

When it comes to planning thinning regimes, the utility of SDMDs really becomes apparent. Typically we start with a problem that is expressed in terms of objectives, which can often be easily translated into feasible treatment options through use of the diagrams. This works particularly well when the objectives are expressed or can be translated into descriptive parameters which are explicitly shown on a particular SDMD.

Let's assume that there is a moderately dense lodgepole pine stand that is currently 6 m tall with a site index of 22 m (reference breast height age 50). We wish to commercially thin (from below) the stand when it is 48 years old (total age) to help overcome a predicted fiber supply deficit, and to carry out the final harvest at the estimated culmination age of 72 years. We also have a target average diameter for our thinning removal of 15 cm to ensure that a large percentage of the thinning volume will provide saw logs. Based on this information, we can deduce the following:

- Top height at final harvest will be 25 m (based on B.C. Ministry of Forests site index curves)
- Top height at the time of thinning will be 19 m
- Quadratic mean diameter (Qmd) of the entire stand at the time of thinning must be considerably larger than that of the thinnings—based on knowledge of similar stands it is estimated that Qmd at the time of thinning must be at least 20 cm.

This and previously stated information can then be plotted on the SDMD (Figure 1).

Critical control points for a desired regime are often determined by the intersection of two iso-lines. For example, the maximum desirable density at final harvest can be determined in this case by the intersection of the 25 m top height line with the lower limit of the Zone of Imminent Competition Mortality (ZICM), as illustrated in Figure 2. Leaving more trees after the CT treatment than suggested from this point will result in the stand starting to self-thin prior to the final harvest, with volume being lost that could have been harvested during the thinning treatment. A second maximum density control point, this time for the stand immediately prior to commercial thinning, is suggested by the intersection of the 20 cm diameter iso-line and the 19 m top height iso-line. In this case, higher-than-suggested densities would result in the target diameter for thinnings not being achieved at the desired thinning date.

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[1] Private consultant, Prince George, British Columbia

Starting at the final harvest control point, a maximum density thinning regime can be plotted (Figure 3), initially by tracing a growth trajectory[1] backward down to the top height iso-line representing the time of thinning (line "a"). Next, the commercial thinning treatment is simulated by tracing along the top height iso-line to the higher pre-thin density (line "b"), and then again tracing backward down a growth trajectory line (line "c") to the top height iso-line representing the current stand top height. This point will indicate the maximum density that can be left in a current PCT treatment (line "d"). Once the regime has been plotted, initial estimates for thinning and final harvest volumes can be calculated (Figure 4).

There is a virtually infinite set of solutions which will satisfy our stated objective using lower densities after both the PCT and CT treatments (Figure 5). Total volume production over the rotation will likely occur at or near the maximum density regime, as long as the trees left after the CT treatment have sufficient crown volume to provide a prompt response to thinning release. Other objectives, such as increased diameter growth or providing light penetration to enhance understory forage production may lead to the need for regimes with lower densities. As will often be the case, there is no single "right" answer to the problem, but the SDMD has provided a framework within which to quickly narrow down the possibilities and to facilitate discussion as to which of many potential solutions might be the most desirable.

Conclusion

Stand density management diagrams are useful tools for crop planning, particularly when used as complements to other G&Y tools such as TASS which have more powerful quantitative abilities. SDMDs provide the silviculturist with a tool to quickly and easily identify a range of options to satisfy stated management objectives. In many cases it allows exploration of potential options for how they might affect other values only marginally associated with crop plan drivers. It is important to recognize however, that the SDMD like any other planning tool is only the framework within which to make decisions—the tool itself does not provide answers.

Major Strengths	Major Weaknesses
• provides for excellent visualization of patterns of stand development • provides a decision making framework within which to evaluate timing and intensity of thinnings • provides a framework within which to compare several density management options • provides a framework within which to share ideas about specific crop plans or more generally, crop plans in relation to stand development patterns • provides a framework within which to assess forest values or operational strategies which closely relate to stand density and stage of development	• logarithmic axes may be misleading • can only represent single species even-aged stands • descriptive parameters are limited to a few stand level attributes • yield predictions are imprecise • yield predictions may be inaccurate after mid- to late-rotation thinning treatments • average stand diameter in particular is overestimated after mid-to-late rotation thinnings—errors increase with thinning intensity. • untrained users often make critical mistakes

Table 1. Strengths and weaknesses of SDMDs as crop planning and growth & yield models.

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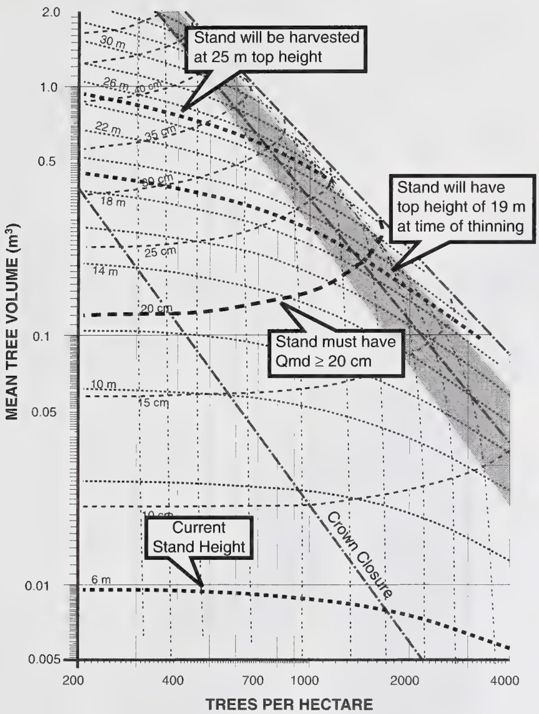
[1] Growth trajectories are labeled on the diagrams as "TASS-Predicted Mortality Curves," and are often referred to as survivorship curves.



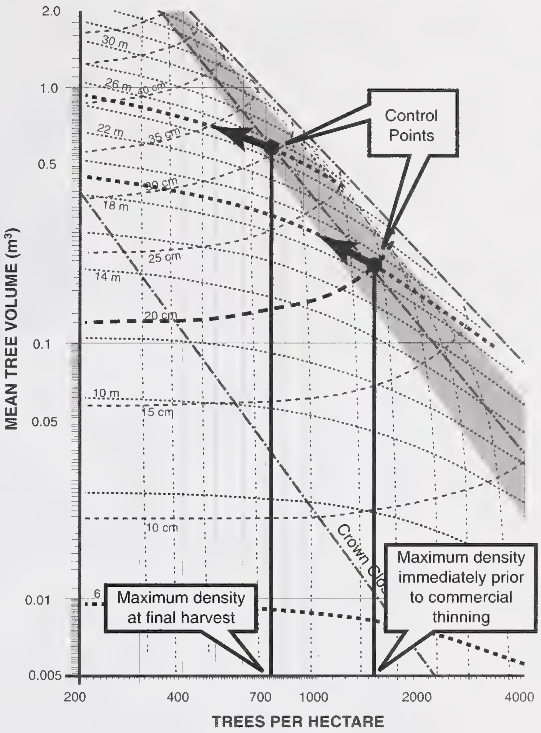
Stand will be harvested at 25 m top height

Stand will have top height of 19 m at time of thinning

Stand must have Qmd ≥ 20 cm

Current Stand Height

Figure 1.



Control Points

Maximum density at final harvest

Maximum density immediately prior to commercial thinning

Figure 2.

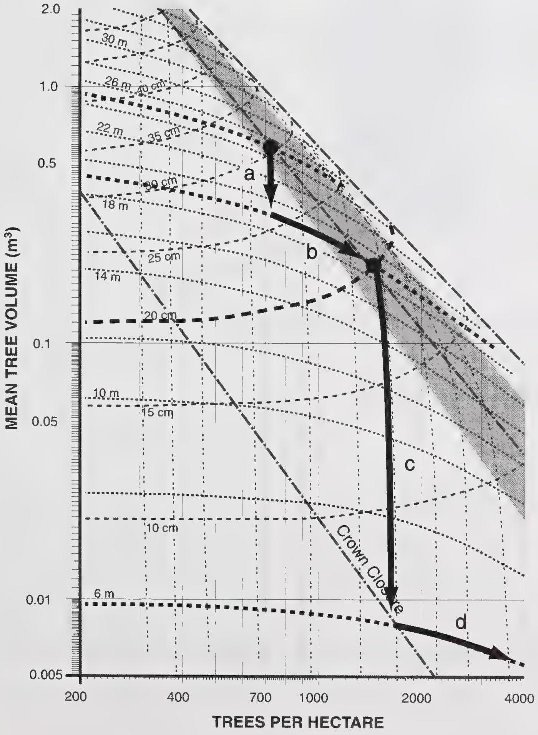
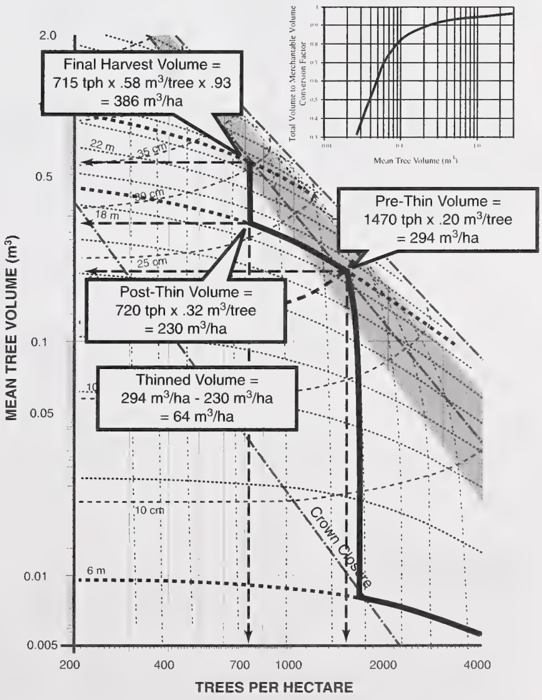


Figure 3.



Final Harvest Volume = 715 tph x .58 m³/tree x .93 = 386 m³/ha

Pre-Thin Volume = 1470 tph x .20 m³/tree = 294 m³/ha

Post-Thin Volume = 720 tph x .32 m³/tree = 230 m³/ha

Thinned Volume = 294 m³/ha - 230 m³/ha = 64 m³/ha

Figure 4.

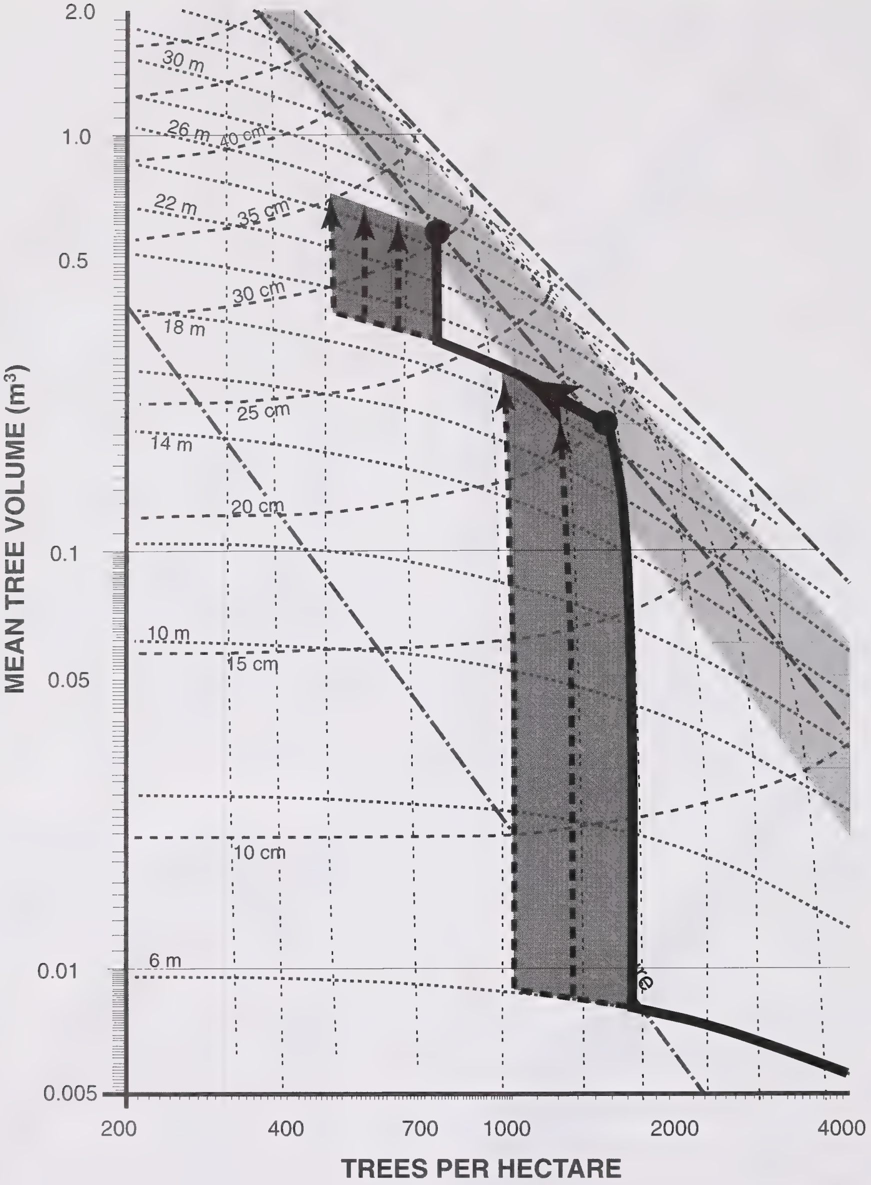


Figure 5.

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Planning stand density management in Alberta. Is PrognosisBC the right tool for the job?

Barry Snowdon[1]

Abstract

PrognosisBC can simulate the development of multi-layered mixed species stands. However, without local calibration, it would of limited use in Alberta. Simulations of hypothetical Lodgepole pine stands, presented in this paper, generated the following stand density management hypotheses:

1) *commercial thinning can provide early access to merchantable timber but will not increase the total amount of timber harvested during the entire rotation from a stand established at low densities; and*
2) *pre-commercial thinning of dense stands will accelerate the movement of the residual trees into larger diameter classes.*

Data from well laid out thinning trials are required to test these hypotheses.

Introduction

PrognosisBC is an adaptation of the US Forest Service individual tree model—the "Forest Vegetation Simulator" from North Idaho.

It is a non-spatial model that can simulate the development of mixed species coniferous stands regardless of stand structure (i.e. complex stands). This model can project a stand from any point in its development, including bareground. A ground based inventory (e.g. Permanent Sample Plots or a timber cruise) is used to describe an existing stand. The model's ability to both compile the inventory, simulate the future dynamics of the stand (e.g. species shifts and breakup) and allow the user to rank alternative partial cutting prescriptions are its great strengths.

PrognosisBC provides the user with a great deal of flexibility in the scheduling of a wide variety of thinning regimes. The user interacts with the model through a menu driven interface that can report results in both graphical and tabular form. A pilot or Beta version of PrognosisBC (version 1.02b) was released for general use in April 1998. It is applicable to Southern Interior of British Columbia.

The applicability of the model to Alberta and some specific simulations for Lodgepole pine are discussed.

The model and its applicability to Alberta

The North Idaho variant of the "Forest Vegetation Simulator" from which PrognosisBC was derived has a proven track record of over 20 years operational use and continued research and development in the United States. PrognosisBC can simulate the development of multi-layered stands comprised of the following species[2]:

western white pine	*(Pinus monticola)*
western larch	*(Larix occidentalis)*
Douglas-fir	*(Pseudotsuga menziesii)*
grand fir	*(Abies grandis)*
western hemlock	*(Tsuga heterophylla)*
western red cedar	*(Thuja plicata)*
lodgepole pine	*(Pinus contorta)*
Engelmann spruce	*(Picea engelmannii)*
subalpine fir	*(Abies lasiocarpa)*
ponderosa pine	*(Pinus ponderosa)*
mountain hemlock	*(Tsuga mertensiana)*

PrognosisBC is an empirical growth model. It projects tree attributes that can be easily measured in the field, it does not attempt to simulate biological processes. Stand development is simulated via eight main sub-models:

1) large tree diameter growth;
2) large tree height growth;
3) large tree crown ratios;
4) small tree diameter growth;
5) small tree height growth;
6) small tree crown ratios;
7) mortality; and
8) regeneration.

For details on these sub-models the reader should refer to Wykoff *et al* 1982, Wykoff 1986 and Robinson 1998. Small trees are defined as trees less than 7.5 cm DBH and large trees are defined as trees 7.5 cm DBH and above. The partition of the treelist into small and large trees is an artifact of the inventory data from which the submodels were built. Initial DBH growth data was obtained by increment coring. Trees smaller than 7.5 cm could not be cored without serious damage being done to the stem. Similarly, height growth information could be easily collected on "small" trees but not on "large" trees.

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[1] British Columbia Ministry of Forests, Victoria, British Columbia

[2] PrognosisBC cannot simulate the development of hardwoods. Complex mixtures of coniferous species can be projected.

Large tree diameter growth rather than large tree height growth drives PrognosisBC. This modeling approach was taken to address concerns over:

- obtaining large tree height growth estimates; and
- obtaining reliable site index estimates in structurally complex stands where the trees often experience height growth suppression.

Within PrognosisBC, plant associations and physical site attributes are used to describe site productivity therefore avoiding the latter problem.

The other terms in the large diameter growth model are:

- current DBH;
- crown ratio (aka "%live crown");
- crown competition factor (CCF); and
- basal area in larger trees (BAL).

The latter three being expressions of tree vigor, stand density and social position respectively.

Tree age is conspicuous by its absence. It is the absence of tree age; the prediction of a periodic diameter increment[3] (which is added to the tree's current DBH); and species specific size, vigor, stand density and social position terms that allows the model to predict the development of complex stands.

Thinning response is not modeled explicitly in PrognosisBC. The same is true for the Ministry of Forests growth and yield model TASS (Polsson *pers. comm.*). In the case of PrognosisBC, increases in diameter growth after a simulated thinning are due to reduction in the CCF and BAL[4] terms.

To expedite a timely release of the model, the calibration included in Release 1.02b was limited to the site productivity terms of the large tree diameter growth equation[5]. Only minor changes were made to the mortality and height growth equations to ensure consistency. When this initial calibration was conducted the PrognosisBC Development Team (PDT) felt there was insufficient BC data to re-estimate all the parameters in each component equation—specifically the small and large tree height growth equations. Because the US parameter estimates would have to be maintained for these equations, the initial calibration was limited to those ecological units common to both BC and North Idaho. Therefore, PrognosisBC would be limited to sites in Alberta that have a North Idaho ecological equivalent. Furthermore, the site productivity terms of the large tree diameter growth equations would need to be calibrated for those Alberta ecological units.

Hence use of PrognosisBC in Alberta would likely be limited to a few ecological units and without local calibration would likely give biased future estimates of yield.

Stand density management simulations

Despite these problems, what information can be gleaned from PrognosisBC regarding stand density management?

Three groups of simulations were conducted to demonstrate the models current behaviour regarding the stand density management of Lodgepole pine. They were not designed to reflect current BC Ministry of Forests stand density management policy. The first two groups of simulations demonstrate the growth response of a hypothetical stand (established at low densities) to commercial thinning. The first group demonstrates the impact of timing; the second group, the impact of thinning intensity. The third group of simulations demonstrate the impact of pre-commercial thinning on the growth of a hypothetical stand established at high densities.

In all cases the site conditions were the same (i.e. MSdk/1 with a site index of approximately 17m for Lodgepole pine). Simulations were limited to even-aged monocultures of Lodgepole pine. All thinnings were conducted from below. Establishment densities, percent removals and the timing of the thinnings are listed in Table 1.

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[3] The increment period is typically 10 years. The simulation of stand development in discrete time steps reduces the precision at which silvicultural treatments can be scheduled.

[4] BAL will only change if the thinning has removed trees larger than the subject tree. Both CCF and BAL have negative parameters.

[5] The size, vigor, stand density and social position parameters were left unchanged. Hence, the partial calibration (included in release 1.02b) was conducted at the stand level, rather than the individual tree level.

Readers who attended the Stand Density Management Conference may realize that the first two groups of simulations presented in this paper differ from those presented at the conference. A bug discovered in the model at the time of writing (now rectified) caused the author to change the thinning treatments specified for these two groups of simulations. The main difference is that the commercial thinnings are scheduled later in the rotation and heavier removals have been specified to ensure that the entries would be economically viable.

To put the PrognosisBC simulations in context, the basal area, merchantable volume, density(sph) and top height statistics were compared to MoF TIPSY statistics from equivalent simulations[6]. If no thinning treatment was specified and an establishment density of 1500 sph was assumed, the PrognosisBC basal area, merchantable volume, density(sph) and top height were 97%, 107%, 93% and 93% of the same statistics reported by TIPSY at 100 years.

Figure 1 depicts the predicted response of the stand to the ***timing*** of a 50% basal area removal conducted mid to late rotation. The amount of merchantable timber removed at the time of thinning is presented in Table 2.

The first group of simulations suggested that by the time the stand had accumulated sufficient merchantable material to make a thinning economically viable, the residual stand would not respond to the increased growing space (Figure 1). The second group of simulations were conducted to demonstrate whether the simulated stand would respond to a lighter thinnings conducted at 80 years (Figure 2). The model's behavior suggested the hypothetical stand would not respond to those lighter thinnings.

These results were not surprising. Goudie and Day (*pers. comm.*) have both found that Lodgepole pine will only respond to thinnings conducted at very young ages. The model's behavior was consistent with these observations.

Figure 3 illustrates why the hypothetical stand did not respond. It depicts the 10 year periodic DBH increment of the tree of median diameter drawn from the hypothetical stand established at 1500 sph. Maximum DBH increment was achieved by 35 years then quickly declined. Our hypothetical stand was far beyond its period of rapid DBH growth by the time merchantable timber could be extracted.

Despite no apparent volumetric gains, the commercial thinning of Lodgepole pine may be a useful silvicultural tool to the forest manager. Commercial thinning can facilitate access to timber that would otherwise not be available due to policy constraints (e.g. green-up/adjacency rules). In addition, the residual stand would also be very uniform in piece size greatly reducing the extraction costs of the final harvest (Whitehead *pers. comm.*).

The results depicted in Figure 3 prompted the third group of simulations. Would PrognosisBC predict merchantable volume gains in response to early stand density management? The results for this group of simulations are presented in Figures 4 and 5. In terms of basal area accumulation (Figure 4), the model predictions were consistent with the principal of "constant final yield" and the work of Pinaar and Turnbull (1973); and Whyte and Woollens (1990). The basal area trajectories for stands established at (or pre-commercial thinned to) a board range of densities converge, provided the site is fully occupied.

If the reader compares the merchantable volume trajectories to the basal area trajectories (see Figure 5 and 4 respectively), he/she should notice that ranking of the treatments differ markedly. In terms of merchantable volume, provided the site was fully occupied, the model predictions suggest that "not thinning" was not the superior option. The model indicated that thinning to 3000 sph, 5000sph and 1000 sph were superior options. Merchantable basal area was plotted to remove height from the volume comparisons (Figure 6).

When height was removed from the comparisons, spacing to 1000 sph produced lower merchantable yields (i.e. merch. basal area) than the "don't thin" scenario after 100 years. In terms of merchantable basal area, the trajectories of the "thin to 3000sph" and "thin to 5000sph" treatments converged by 120 years (Figure 6). The apparent separation of the 3000 sph and 5000 sph treatments in terms of merchantable volume (Figure 5) at 120 years was therefore due to height differences. Similarly, the convergence of the "thin to 1000sph" treatment and the "don't thin" scenario at 120 years (rather than divergence) was due to height differences.

Within PrognosisBC (and its North Idaho parent) stand density affects height growth indirectly. The greater the stand density, the slower the diameter growth and in turn the slower the height growth of individual trees. Time constraints have prevented the author from investigating whether this behavior is just an artifact of the height growth model formulation or an observable phenomena. Height growth aside, these model simulations generated the following hypotheses concerning the response of

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[6] Assuming a site index of 17m, an OAF1 and OAF2 of 15% and 5% respectively and the same establishment density as the PrognosisBC simulation.

Lodgepole pine stands to thinning treatments:

1) commercial thinning can provide early access to merchantable timber but will not increase the total amount of timber harvested during the entire rotation from a stand established at low densities; and
2) pre-commercial thinning of dense stands will accelerate the movement of the residual trees into larger diameter classes.

Conclusions

Without local calibration, the current version of PrognosisBC is not directly applicable to Alberta. It is the authors opinion that Alberta's growth and yield needs would better addressed by industry and government devoting a substantial effort to the MGM growth model developed with Alberta data by Dr. Stephen Titus from the University of Alberta. MGM has a quite similar architecture to PrognosisBC so it should be quite flexible in the stand structures that it can project.

The use of growth models to predict thinning response is problematic. Most growth and yield models currently available (including TASS, PrognosisBC, MGM and SPS) do not contain explicit, empirically derived thinning response relationships and therefore can only be used to generate hypotheses about thinning response. Data from well laid out thinning trials are required to test these hypotheses.

Tables and figures

Simulation group	establishment density	% removal/residual density	timing of the thinning
1	1,500 sph	don't thin	N/A
	"	50% basal area removal	70 years
	"	" " " "	80 "
	"	" " " "	90 "
	"	" " " "	100 "
	"	" " " "	110 "
2	"	10% basal area removal	80 years
	"	20% " " "	"
	"	30% " " "	"
	"	40% " " "	"
	"	50% " " "	"
3	10,000 sph	don't thin	N/A
	"	space to 5000 sph	10 years
	"	" " 3000 sph	"
	"	" " 1000 sph	"
	"	" " 500 sph	"

Table 1: Establishment densities, percent removals and the timing of the thinnings for hypothetical Lodgepole pine stands.

Stand age at time of thinning (years)	Merch. Volume removed (17.5cm, + m³/ha)
70	32[7]
80	78
90	121
100	155
110	178

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[7] It is debatable whether a 50% basal area removal at 70 years would be considered commercial.

Table 2: The amount of merchantable timber removed at the time of thinning for the first group of simulations described in Table 1.

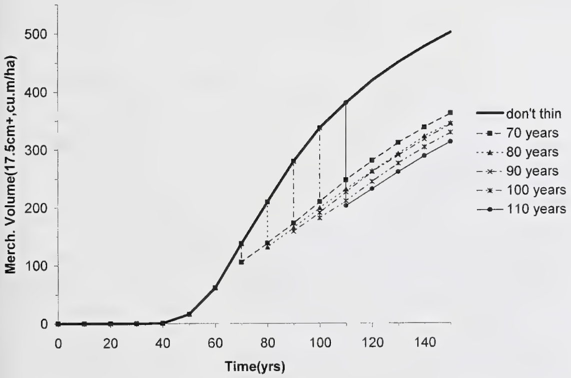

Figure 1: The impact of mid to late rotation commercial thinning on merchantable volume accumulation. (MSdk/1 Lodgepole pine stand established at 1500 sph, site index approximately 17m, 50% basal area removal).

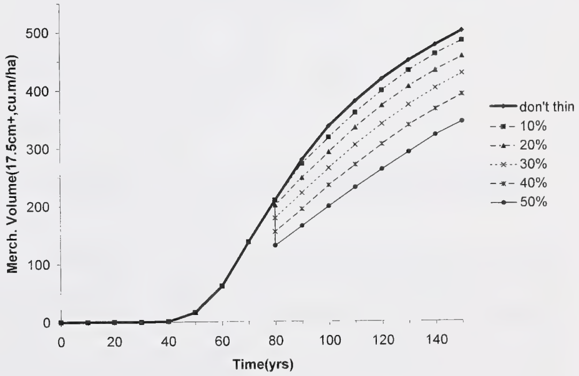

Figure 2: The impact of commercial thinning intensity scheduled at 80 years on merchantable volume accumulation. (MSdk/1 Lodgepole pine stand established at 1500 sph, site index approximately 17m).

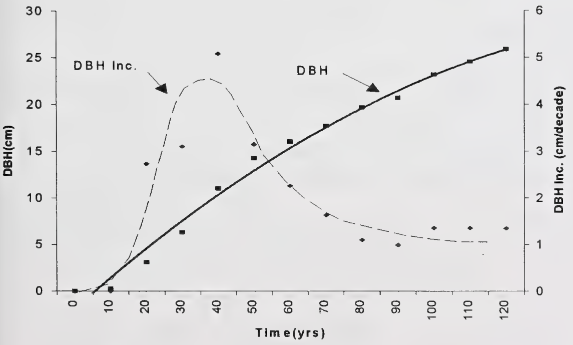

Figure 3: The diameter and 10 year periodic DBH increment of the tree of median diameter. (MSdk/1 Lodgepole pine stand established at 1500 sph, site index approximately 17m)

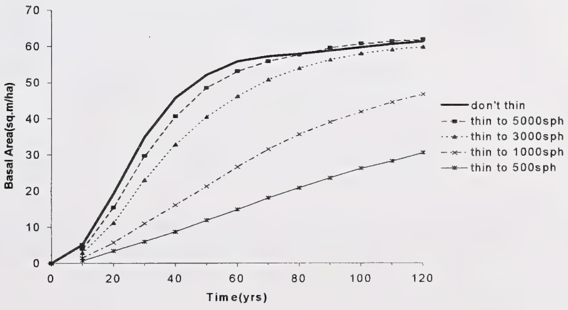

Figure 4: The impact of (pre-commercial) thinning intensity scheduled at age 10 on basal area accumulation. (MSdk/1 Lodgepole pine stand established at 10,000 sph, site index approximately 17m)

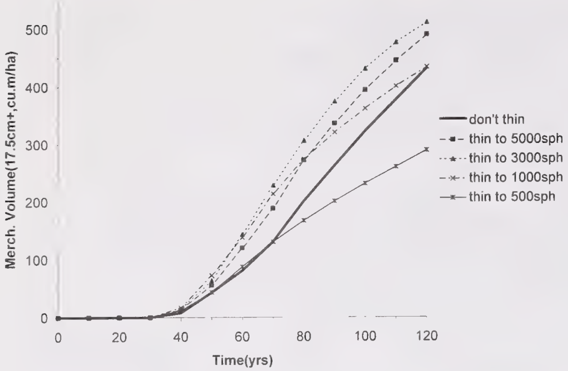

Figure 5: The impact of (pre-commercial) thinning intensity scheduled at age 10 on merchantable volume accumulation.(MSdk/1 Lodgepole pine stand established at 10,000 sph, site index approximately 17m)

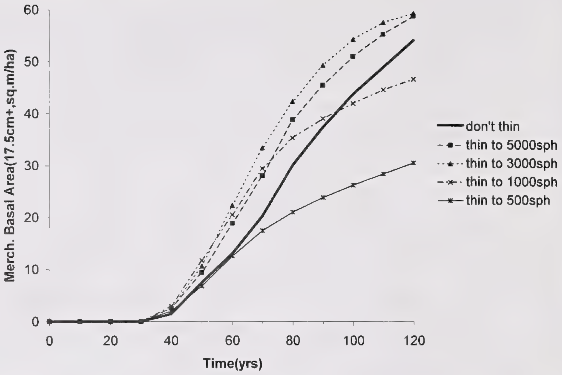

Figure 6: The impact of (pre-commercial) thinning intensity scheduled at age 10 on merchantable basal area accumulation.(MSdk/1 Lodgepole pine stand established at 10,000 sph, site index approximately 17m)

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Day, Robert; Faculty of Forestry, Lakehead University, Thunder Bay Ontario.

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Polsson, Ken; Stand Modeling Analyst, British Columbia Ministry of Forests, Victoria, British Columbia.

Whitehead, Roger; Program Head, Silvicultural Systems Research, Natural Resources Canada, Victoria, British Columbia.

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Density Management Diagrams
... Tools and Uses

Murray E. Woods[1]

Density management diagrams (DMDs) have been developed for a wide range of North American tree species. They have proven to be an excellent exploratory tool in understanding the interaction of density, average tree volume and diameter within a forest stand. DMDs have been recently promoted as a suitable tool for determining timing and extent of stand thinning interventions. Unfortunately, the success of their adoption, due to their complexity, has been limited. To facilitate their acceptance and utilization, simple to use, interactive software has been developed. This paper will provide a brief review of the ***Ontario Density Management Diagram – ODMD*** *software (Beta version).*

Introduction

Density management diagrams (DMDs) for a range of species have been published in North American literature over the past two decades. Drew and Flewelling (1979) described and presented the generally adopted format for DMDs for their coastal douglas-fir *(Pseudotsuga menziessii* (Mirb.) Franco var. *menziesii)* plantation diagram. This work spurred on the development of DMDs for black spruce *(picea mariana* (Mill.) B.S.P.) (Newton and Weetman, 1993), jack pine *(Pinus banksiana* (Lamb.) (Archibald and Bowling, 1995), interior douglas-fir, lodgepole pine *(Pinus contorta* Dougl.), white spruce *(Pica glauca* (Moench) Voss) (Farnden 1996), red pine *(Pinus resinosa* Ait.) and white pine *(Pinus strobus* L.) (Smith and Woods, 1997).

DMDs are graphical diagrams that help resource managers understand the dynamic relationship between stand density and tree size as they relate to zones of optimum growing conditions and zones of competition induced mortality. Density management diagrams enable prescription development for initial plantation establishment or as a guide (with some simple field measurements) to help managers determine stand thinning, timing and intensity.

Theoretical Background

Density management diagrams are based on the –3/2 power law of self-thinning (Yoda et al. 1963). This law or rule states that "*...for any given density, there is a maximum average biomass that an individual plant can attain...*" and "*...any further increase in average plant biomass can only be achieved at a lower density, therefore some individual plants must die.*" The diagram relates changes in mean plant size to stand density using logarithmically transformed axis. Although originally developed with grass species, this relationship has been found to work well with forest crops. A simplified representation of a DMD with two stand development trajectories (from Smith and Woods 1997) along with its underlying concepts is presented in Figure 1.

Four parallel density–dependent lines are shown (Figure 1):

- maximum size–density (or upper self–thinning /full stocking) line;
- mortality initiation (lower self–thinning) line;
- maximum stand production initiation line; and,
- crown closure line.

Technology Transfer

Application of these diagrams by resource managers in Ontario has been minimal. It is assumed that their complexity has limited their adoption into the silvicultural decision making process. Figure 2 illustrates a completed density management diagram. In addition to the relative-density lines and zones described in Figure 1, Figure 2 presents additional diameter and top height isolines added to provide some field functionality to the tool. Unfortunately, this functionality comes at the price of making the DMD look more intimidating to the users.

It was thought that with instruction, this initial intimidation and reluctance to use the DMD with its multiline presentation could be overcome. Unfortunately, in most cases, the time required in calculating the values on the diagram with the aid of a ruler and calculator has proven to be a limiting feature.

Figure 3 outlines the step-by-step process that is undertaken to manually develop a thinning crop plan on a DMD. With this amount of work and time

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commitment, a good science based tool has seen very little of any use by resource managers. Stand density management decisions were either being "*best-guessed*" or not being considered as an appropriate strategy. Based on this lack of use, many stands that were in a severe state of over-stocking were not being treated appropriately.

Ontario Density Management Diagram Software

In an effort to have more people utilize DMD principles in the development of silvicultural crop plans, intuitive and interactive software has been developed. The software "*Ontario Density Management Diagram—ODMD*" (Woods et al, 1998) (Figure 4) is a package that allows quick stand density management "gaming" scenarios to be calculated and evaluated. In what can take many minutes to calculate by hand on a paper version of a DMD, the ODMD software is able to provide accurate answers in seconds.

The program is written in Visual Basic and runs in the Windows 95 or the Windows 98 operating system.

The ODMD software has been developed in a book style format. Tabs along the right hand margin of the screen identify pages within the book. Tabs appear and disappear as user interactive choices are selected throughout the program.

The title page is an introductory screen that provides the user the first look at the "book" design of the software. Other tabs can be selected and explored as they become activated and appear on the right hand edge of the form.

As in the case with most programs written in the Windows‰ framework, a comprehensive HELP system has been designed and built into the ODMD software (Figure 5). A "Table of Contents" system as well as a search "index" system is provided. Attribute definitions and detailed technical reports are provided on-line and can be printed at the user's request.

The Getting Started tab (Figure 6) accesses the key screen for the ODMD software. In order to move forward through the program three selections must be made:

- Region of the province
- Forest Type:
  Plantations or Natural
  Stands, using existing known stand parameters or enter field plot data.
  Species: white pine, red pine, jack pine, black spruce (draft)

Plantation Establishment

If a new plantation is the modeling choice (Figure 7), the required information to proceed includes an estimate of site quality (site index), a spacing factor or planting density (each resetting the other to their corresponding value). Another method to set these parameters is to enter a desired average stand diameter at the time of required first thinning (relative-density = 0.55 point).

Specific soil/site relationships and other species suitability work for Northwestern Ontario has been built into the software. If soil condition or an alternate species was taken from the site, the software provides suitable site quality estimates to plan the next forest crop.

Computed stand estimates for top-height and age are presented for the plantation's recommended point of thinning. All values can be viewed graphically by selecting the *DMD Graph* Tab.

Known Stand Parameters

Direct entry into the ODMD model can be accomplished if measurements of stand density, quadratic mean diameter (DBHq), age and top-height are known (Figure 8). The three required variables for the user to enter are stand age, density and DBHq. The model computes stand top-height and based on the entered stand age, site index. An average spacing and basal area is computed. An indication of the stand's competitive status is displayed as one of the zones introduced and explained earlier.

Because the ODMD is an average stand model, users should ensure that the model's estimation of stand top-height is similar to what was measured in the field. A measurement of model confidence can be attained by how similar the estimated top-height is to the actual measured top-height value.

All values can be viewed graphically by selecting the *DMD Graph* Tab.

Sample Plot Data

Selecting the *Sample Plot Data* Tab allows the user to enter diameter measurements from fixed area plots of known size and stand age. Stand summary values for each plot entered are presented and can be displayed on the ODMD by selecting the DMD Graph Tab. Aggregations of similar plots located within a stand can be made with this option. Individual crop plans can be completed for stratified areas within an individual plantation or natural stand.

DMD Graph

Entered stand data are presented on an electronic DMD (Figure 9). The diagram has been visually simplified by removing the diameter and top-height isolines. In its place a dynamic pointer has been added. As you move the pointer (a hand shaped cursor) computed stand values are presented on the upper right hand portion of the screen. Top-height, diameter isolines and zones of stand status can be displayed if chosen.

Thinning can be accomplished on the diagram by clicking with the left mouse button anywhere on the diagram above the green line (indicating a harvest) and outside *the "Zone of Imminent Competition and Mortality."* Multiple thinning interventions can be simulated on the diagram. Any or all thinnings can be removed by clicking on the "*Undo*" button. Selecting and clicking on the "Reset" button will allow the user to start over from the originally entered parameter position. A copy of the diagram can be printed to any connected printer by selecting the print button.

Table Summary

A tabular summary of pre- and post-thinning scenarios can be viewed and printed (Figure 10). This table can be personalized and added to the crop plan file.

Summary

The use of density management diagrams by resource managers in Ontario has been limited. Some of the reluctance to use this tool has been due to the perceived complexity of the paper based multi-line diagram form. The recent development of the ODMD software now allows resource managers to quickly evaluate appropriate silvicultural options by "gaming" with the aid of a few mouse clicks. It is hoped that density management diagram literature will be dug out from the bottom of the filing cabinets, dusted off and used in the development sound silvicultural crop plans.

Figures and tables

Maximum Size–Density Line

The Maximum Size–Density Line defines the limit for any combination of mean size and stand density. In theory the slope of this line is –3/2 and is assigned a relative density of 1.00.

Mortality Initiation Line

Mortality increases significantly for a stand once it crosses the Mortality Initiation Line (relative density = 0.55). Between the Maximum Size–Density Line and the Mortality Initiation Line trees undergo the highest rate of density–dependent mortality and enter a self–thinning phase. This zone is referred as *the Zone of Imminent Competition Mortality* and stands are considered to be over–stocked in this region of the diagram.

Maximum Stand Production Zone

Stands that lie between relative densities of 0.40 and 0.55 are said to exist within the *Zone of Optimum Density Management*. Stands located within this zone are considered optimally stocked, and stand production is estimated to be at maximum (Langsaeter 1941).

Crown Closure Line

The relative density line (rd=0.15) defines the boundary of the approximate crown closure line. It is at this combination of size and density where stands are estimated to have achieved crown closure.

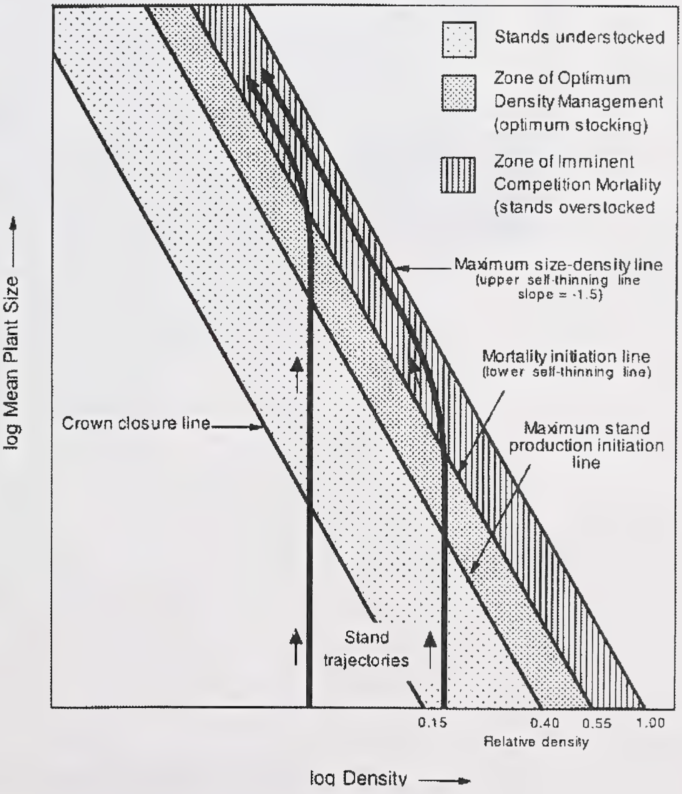

Stands understocked
Zone of Optimum Density Management (optimum stocking)
Zone of Imminent Competition Mortality (stands overstocked
Maximum size-density line (upper self-thinning line slope = -1.5)
Mortality initiation line (lower self-thinning line)
Maximum stand production initiation line
Crown closure line
Stand trajectories
log Mean Plant Size
0.15
0.40
0.55
1.00
Relative density
log Density

Figure 1: Simplified

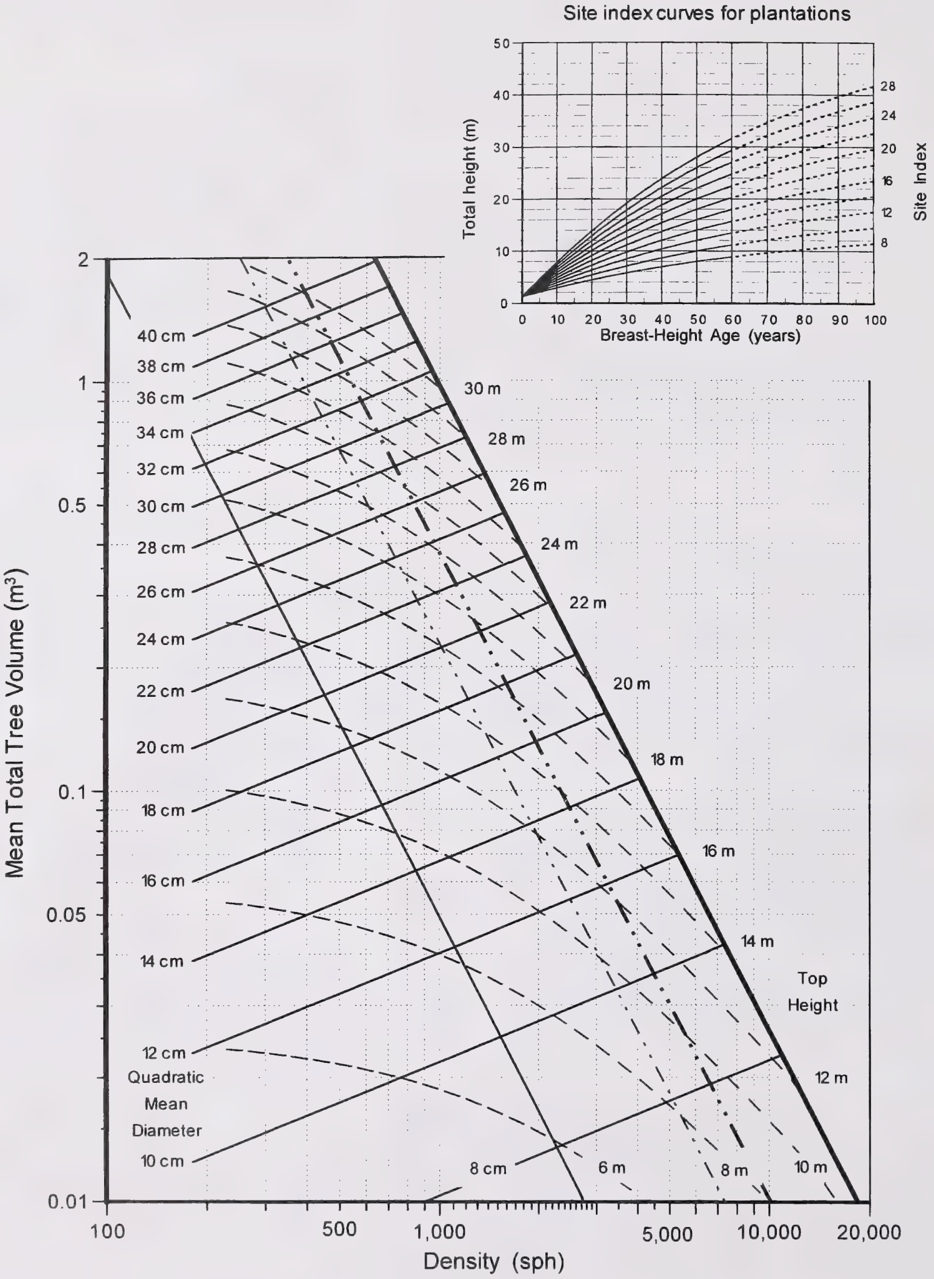
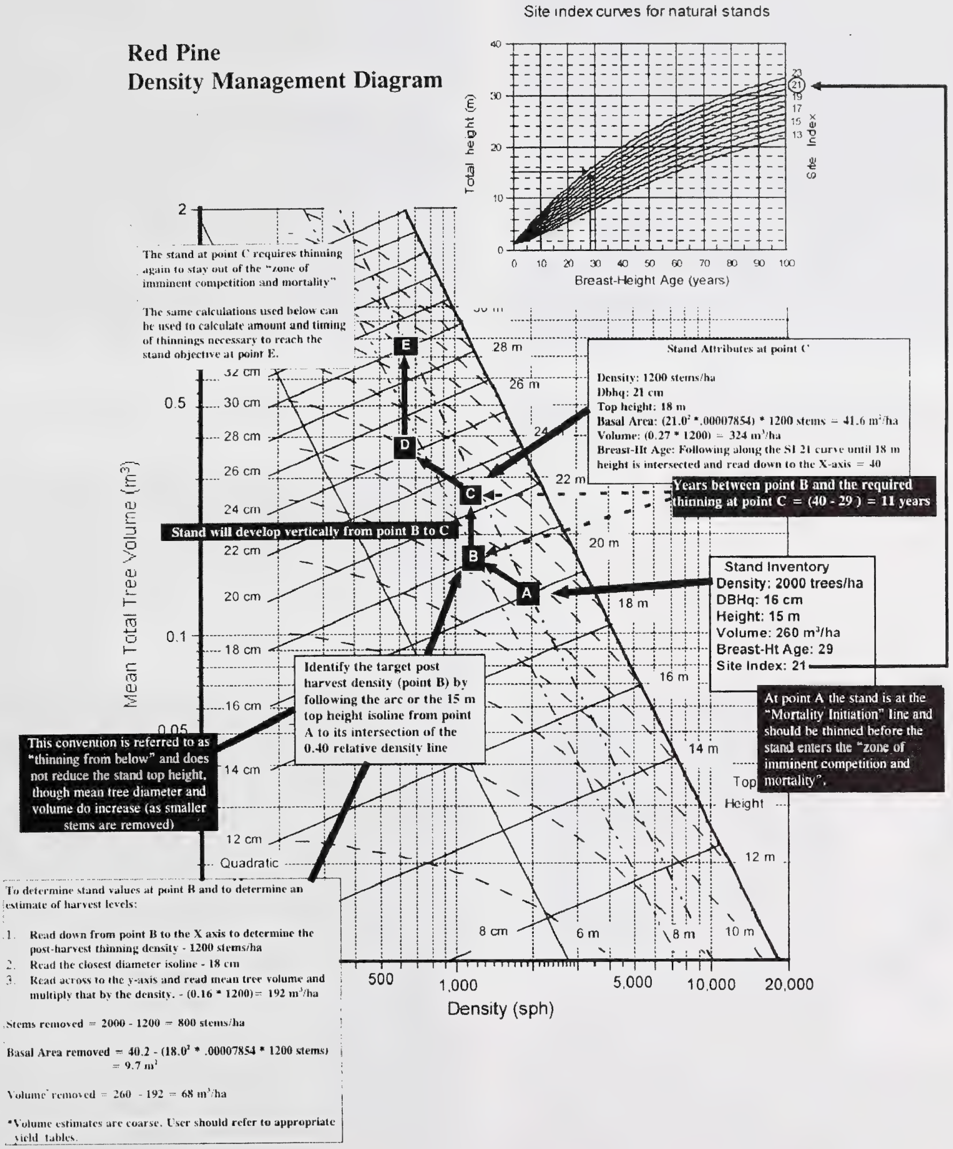


Figure 2: Red Pine Density Management Diagram



Red Pine
Density Management Diagram

The stand at point C requires thinning again to stay out of the "zone of imminent competition and mortality"

The same calculations used below can be used to calculate amount and timing of thinnings necessary to reach the stand objective at point E.

Stand Attributes at point C

Density: 1200 stems/ha
Dbhq: 21 cm
Top height: 18 m
Basal Area: (21.0² *.00007854) * 1200 stems = 41.6 m²/ha
Volume: (0.27 * 1200) = 324 m³/ha
Breast-Ht Age: Following along the SI 21 curve until 18 m height is intersected and read down to the X-axis = 40

Years between point B and the required thinning at point C = (40 - 29) = 11 years

Stand will develop vertically from point B to C

Stand Inventory
Density: 2000 trees/ha
DBHq: 16 cm
Height: 15 m
Volume: 260 m³/ha
Breast-Ht Age: 29
Site Index: 21

Identify the target post harvest density (point B) by following the arc or the 15 m top height isoline from point A to its intersection of the 0.40 relative density line

At point A the stand is at the "Mortality Initiation" line and should be thinned before the stand enters the "zone of imminent competition and mortality".

This convention is referred to as "thinning from below" and does not reduce the stand top height, though mean tree diameter and volume do increase (as smaller stems are removed)

To determine stand values at point B and to determine an estimate of harvest levels:

1. Read down from point B to the X axis to determine the post-harvest thinning density - 1200 stems/ha
2. Read the closest diameter isoline - 18 cm
3. Read across to the y-axis and read mean tree volume and multiply that by the density. - (0.16 * 1200)= 192 m³/ha

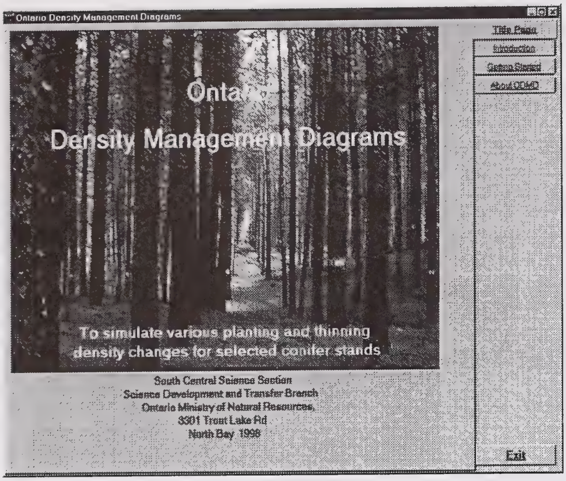
Stems removed = 2000 - 1200 = 800 stems/ha

Basal Area removed = 40.2 - (18.0² * .00007854 * 1200 stems)
= 9.7 m²

Volume* removed = 260 - 192 = 68 m³/ha

*Volume estimates are coarse. User should refer to appropriate yield tables.

Figure 3: Development of a manual thinning crop plan for Red Pine

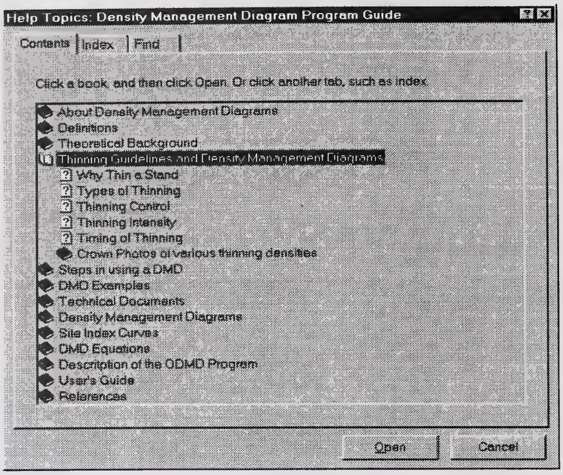


Ontario
Density Management Diagrams

To simulate various planting and thinning density changes for selected conifer stands

South Central Science Section
Science Development and Transfer Branch
Ontario Ministry of Natural Resources,
3301 Trout Lake Rd
North Bay 1998

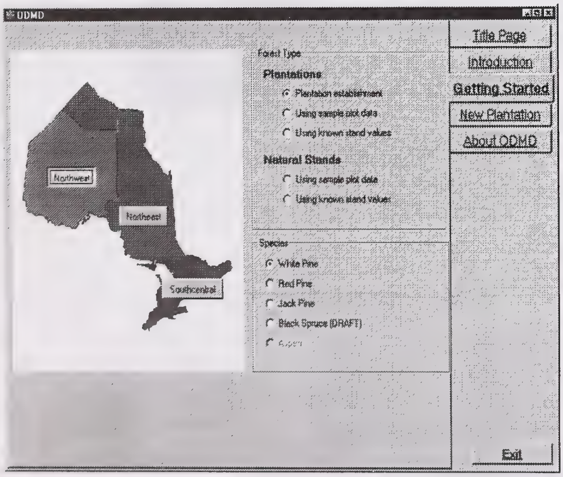
Figure 4: Ontario Density Mangement Diagram — ODMD



Click a book, and then click Open. Or click another tab, such as Index.

- About Density Management Diagrams
- Definitions
- Theoretical Background
- Thinning Guidelines and Density Management Diagrams
  - Why Thin a Stand
  - Types of Thinning
  - Thinning Control
  - Thinning Intensity
  - Timing of Thinning
  - Crown Photos of various thinning densities
- Steps in using a DMD
- DMD Examples
- Technical Documents
- Density Management Diagrams
- Site Index Curves
- DMD Equations
- Description of the ODMD Program
- User's Guide
- References

Figure 5: HELP — Table of Contents



Forest Type

Plantations

● Plantation establishment
○ Using sample plot data
○ Using known stand values

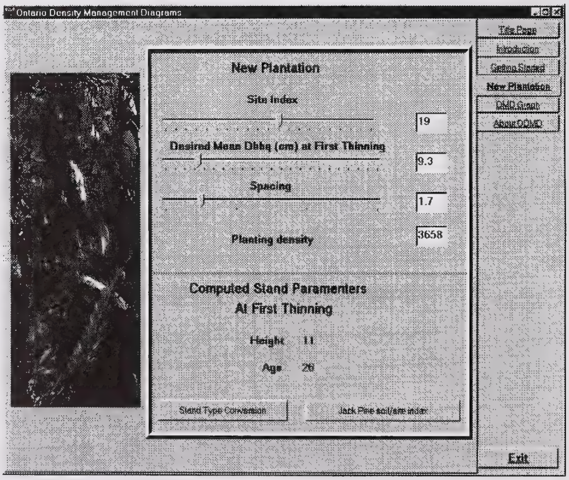
Natural Stands

○ Using sample plot data
○ Using known stand values

Species

● White Pine
○ Red Pine
○ Jack Pine
○ Black Spruce (DRAFT)
○ Aspen

Figure 6: Getting Started menu options



New Plantation

Site Index: 19

Desired Mean Dbhq (cm) at First Thinning: 9.3

Spacing: 1.7

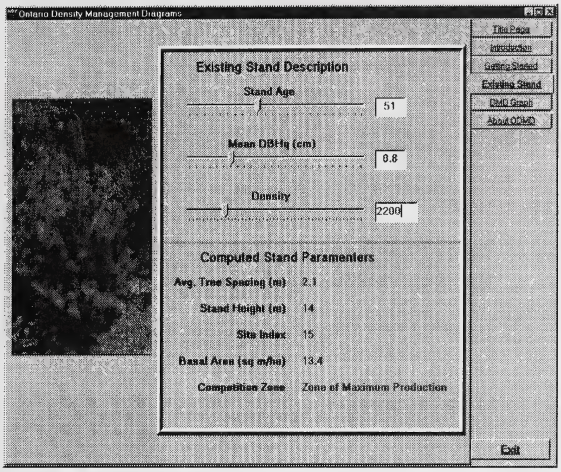
Planting density: 3658

Computed Stand Paramenters At First Thinning

Height 11

Age 26

Figure 7: Plantation Establishment



Existing Stand Description

Stand Age: 51

Mean DBHq (cm): 8.8

Density: 2200

Computed Stand Paramenters

Avg. Tree Spacing (m): 2.1

Stand Height (m): 14

Site Index: 15

Basal Area (sq m/ha): 13.4

Competition Zone: Zone of Maximum Production

Figure 8: Known Stand Parameters

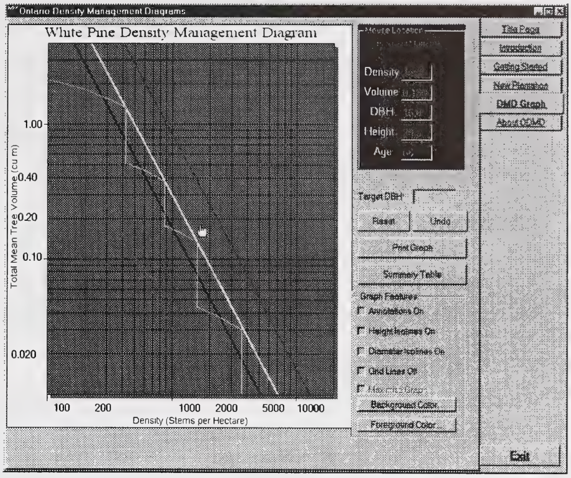
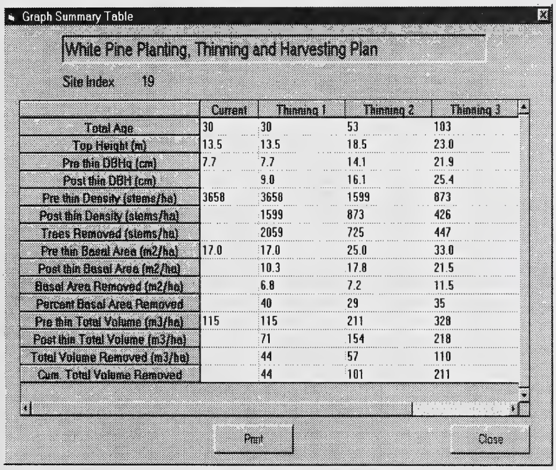


Figure 9: DMD Graph



White Pine Planting, Thinning and Harvesting Plan

Site Index 19

	Current	Thinning 1	Thinning 2	Thinning 3
Total Age	30	30	53	103
Top Height (m)	13.5	13.5	18.5	23.0
Pre thin DBHq (cm)	7.7	7.7	14.1	21.9
Post thin DBH (cm)		9.0	16.1	25.4
Pre thin Density (stems/ha)	3658	3658	1599	873
Post thin Density (stems/ha)		1599	873	426
Trees Removed (stems/ha)		2059	725	447
Pre thin Basal Area (m2/ha)	17.0	17.0	25.0	33.0
Post thin Basal Area (m2/ha)		10.3	17.8	21.5
Basal Area Removed (m2/ha)		6.8	7.2	11.5
Percent Basal Area Removed		40	29	35
Pre thin Total Volume (m3/ha)	115	115	211	328
Post thin Total Volume (m3/ha)		71	154	218
Total Volume Removed (m3/ha)		44	57	110
Cum. Total Volume Removed		44	101	211

Figure 10: Summary Table

Literature Cited

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Yoda, K.; Kira, T; Ogawa, H.; Hozumi, K. 1963. Self-thinning in overcrowded pure stands under cultivated and natural conditions. J. Biol. (Osaka City Univ., Japan) 14:107-129.

The Stand Projection System: Description And Application to Stand Density Management

Terry D. Droessler[1]

Introduction

The Stand Projection System (SPS) was developed by James D. Arney. The distribution of source code for early versions has led to customized applications and some confusion. The SPS I will be talking about is owned, maintained and updated by Mason, Bruce & Girard, Consulting Foresters in Portland, Oregon.

The SPS Taper System

The SPS Library contains the coefficients and parameters used in calculating volumes, growth rates and mortality for individual species in defined geographic areas. Heights in the SPS system are often expressed in terms of "relative height (Rh)," which is defined as:

$Rh = (H - 4.5) / (TH - 4.5)$

where:

H = height above ground to any point on the stem, in feet,
TH = total height of the tree, in feet,
4.5 is breast height, in feet.

Likewise, diameters are expressed in terms of "relative diameter":

$Rd = (DIB / DBH_{ib})$

where:

DIB = diameter inside bark at any point,
DBH_{ib} = diameter at breast height, inside bark.

SPS uses relative height to 80 percent of DBH to classify stem form.. This classification was developed by Arney and Paine (1972) from earlier work by Grossenbaugh (1954). We refer to the Rh_{80} for a tree as its "taper class."

In terms of the equations given above, relative height to 80 percent of DBH is defined:

$Rh_{80} = (H_{80} - 4.5) / (TH - 4.5)$

where:

H_{80} = height from ground, in feet, to the point where $Rd = 0.80$,
TH = Total height in feet.

Rh_{80} can be derived two ways in SPS:

1. By measurement—Cruisers measure height to the point on the bole where DOB is 80 percent of the tree's DBH.
2. By an equation—In the absence of measurements, SPS can use a prediction equation developed by Arney (1987):

$Rh_{80} = b_0 + b_1 * (DBH / TH) + b_2 * (TH^2) + b_3 * DBH + b_4 * DBH^2$

where:

b_0, b_1, b_2, b_3, b_4 are regression coefficients estimated for a species in a particular region. These are stored in the SPS library file (SPS.LIB).
DBH = diameter at breast height,
TH = total height.

---

[1] Mason, Bruce & Girard, Inc.

For Douglas-fir in SPS region 1, which covers the coast range and Cascades in Oregon and Washington, the coefficients are:

$b_0 = 0.4779$, $b_1 = -1.105$, $b_2 = -0.00000153$, $b_3 = 0.0$, $b_4 = 0.0$

SPS Taper Functions

Tree volumes in SPS are computed using tree taper functions. The standard SPS taper functions are based on the relative height equation:

$Rh_i = b_0 * (1.0 - \exp(b_1 * (1 - Rd_i)))^{b2}$

where:

b_0, b_1, b_2 are coefficients estimated by regression for a species, region and taperclass.

Rd_i = relative diameter at i^{th} point on the tree.

The figure below shows a typical set of relative height curves for Douglas-fir.

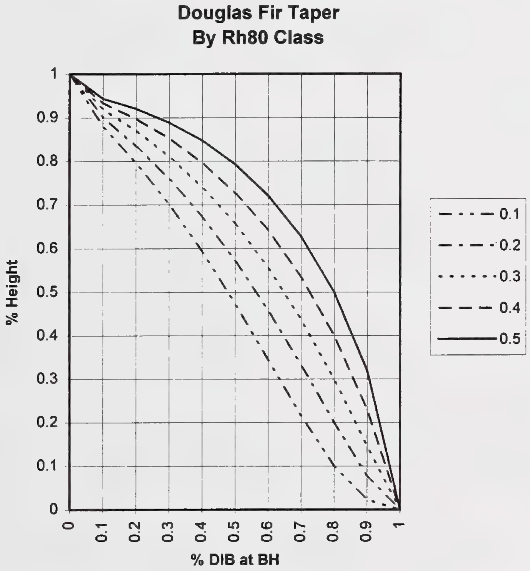

Figure 1. Typical Wood Ratios

In practice, the SPS library stores Rh_i values in a table by taper class and relative diameter. When SPS needs a height, it looks up the relative height in the table. For example, calculate height a 5" top DIB for the following tree.

DIB at BH = 24"
Total Height = 125'
Taper Class = 34%
We want height to relative diameter = 5/24 = 0.208
Interpolating we get RH = 0.8775
So height to 5" DIB = .8775*(125-4.5) + 4.5 = 110.23 Ft

Note that although the standard SPS taper functions are based on the equation given above, this table lookup method makes it easy to put any taper function into the SPS library.

Taper Class	Percent of DBH_{ib}										
	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	0%
10%	.000	.023	.100	.215	.344	.473	.593	.701	.796	.880	1.00
20%	.000	.077	.200	.332	.458	.572	.673	.761	.836	.901	1.00
30%	.000	.146	.300	.437	.556	.657	.741	.812	.871	.920	1.00
40%	.000	.229	.400	.534	.642	.728	.797	.853	.898	.934	1.00
50%	.000	.320	.500	.627	.721	.793	.848	.889	.921	.944	1.00

Table 1. Example table of Relative Height by Taper Class and Relative Diameter

SPS Bark Thickness Equations

Standard SPS bark thickness is based on analysis by Arney (1987). SPS uses a wood ratio, defined as

Wood Ratio = (DIB / DOB)

where:

DIB is diameter inside bark at some point on the stem
DOB is diameter outside bark at the same point.

The following graph shows typical wood ratios.

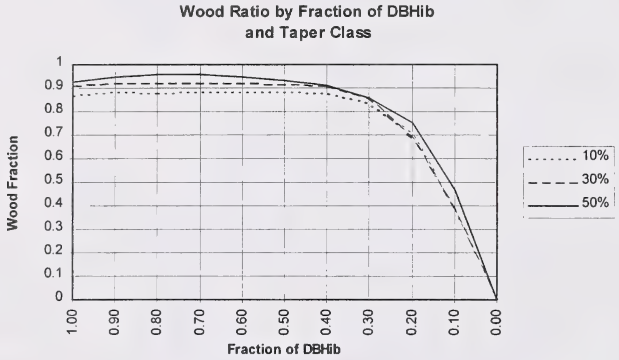

Figure 2. Relationships between Volume and Heights

SPS indexes wood ratios using an access equation to predict wood ratio at 80% of DBH:

$$WR_{80} = b_0 + (b_1 * TH) + (b_2 / A) + (b_3 * DBH) + (b_4 / DBH)$$

where:

b_0, b_1, b_2, b_3, b_4 are regression coefficients estimated for a species in a particular region. These are stored in the SPS library file (SPS.LIB).

TH = total height of the tree, in feet,
A = Age in years
DBH = Diameter at breast height, outside bark

For Douglas–fir in SPS region 1

$b_0 = 0.8639$, $b_1 = 0.0001786$, $b_2 = 2.081$, $b_3 = 0.0$, $b_4 = 0.0$

For example,

DBH = 26”
Total Height = 125’
Age = 85

Substituting these values in the access equation gives:

$$WR_{80} = 0.9107$$

SPS uses the access equation and the wood ratio table DBH_{ib} to go from DBH_{ob} and taper height to a DBH_{ib} and taper class. This is somewhat complex calculation and is not illustrated here.

Row	**Percent of DBH_{ib}**										
	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	0%
1	.868	.882	.879	.883	.884	.886	.880	.838	.705	.379	.000
2	.910	.919	.920	.920	.919	.918	.911	.857	.690	.382	.000
3	.924	.948	.960	.957	.945	.931	.913	.858	.753	.466	.000

Table 2. Wood ratios by taper class and percent of DBH_{ib}

Site Index

SPS uses site index to help determine growth rates. SPS uses site index to set a point on the HEIGHT/DBH curve when there is not enough data to estimate the relationship directly. SPS also calculates SI from measured age-height pairs in the cruise data.

Site index curves in SPS have been classified using Zeide's (1978) two-point technique. Heights are expressed as a percentage of height above DBH at 50 years and a Growth Type value is assigned to each site class. The Growth Type values are used to determine the coefficients of the equation:

$$HEIGHT = b_1 * S + * (1 - \exp(b_2 * A))^{b3} + 4.5$$

where:

b_1, b_2, b_3 are coefficients
S is height at age 50 minus breast height (i.e.: SI - 4.5)
A is age.

Site Class	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**
Growth Type	6.23	6.23	6.23	6.23	6.26	6.25	6.27	6.30	6.31	6.35	6.37	6.38

Table 3. Example of Growth Types from SPS.LIB

The SPS library also stores a relative Site Index for every species. This assumes that SI for any species SI can be expressed as a fraction of the SI for the first species in the library. For SPS region one, Douglas-fir is the first species, and has a relative SI of 1.000. Relative SI values range from 1.050 for Grand Fir to 0.900 for Western Hemlock.

Age To Breast Height

SPS cruising measures age at breast height, which is later adjusted to total age. To do this, the SPS library carries a table of years to breast height by Site Class.

Site Class	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**	**130**
Years to BH	13	12	12	11	11	10	10	9	9	8	8	7

Table 4. Example of Age to Breast Height data from SPS.LIB

Inter-Tree Status

The SPS library contains information used to relate trees to each other.

The relative site index is "relative" to the first species in the SPS library. Douglas fir is the first species in the SPS region one library, and so has a relative site index of 1. Western Hemlock is the second species and has a relative site index of 0.9. This means that Western Hemlock's site index will be 90% of Douglas fir's.

Tolerance is used in calculating the crown competition in the stand. The tolerance coefficient for Douglas fir in SPS region one is -0.6.

SPS both estimate crown width from tree DBH using the equation:

$$CW = b_1 * b_2 * (1 - \exp(b_3 * DBH))$$

Where:

b_1, b_2, b_3 are coefficients.
DBH is diameter at breast height.

For Douglas fir in SPS region one $b_1 = 3.91$, $b_2 = 81.0$, and $b_3 = -0.025$

Mortality in SPS is based on a competition factor for each line in DBHCLASS. The SPS library contains three parts of that calculation: An index to equation form, coefficients for computing maximum competition factor, and an absolute maximum competition factor. For Douglas fir in SPS region one, these values are 1, -3.5510, 0.4405, and 400.0 respectively. See the sections on DBH and height growth for more details.

The crown competition factor expresses the fraction of the stand area covered by tree crowns and is calculated by the summing the individual crown areas:

$$CCF = (p / 4) * (S (CW^2)) / 43560$$

Crown competition factors can exceed one, in which case the ground is covered more than once.

DBH Growth In SPS

Description

For each 12-foot top height increment period, the diameter increment function provides an estimate of the relative diameter increment that could occur. This equation is a function of initial relative tree size and stand density. The form of the equation is:

$$Dinc/Tinc = B1 * (CCF/100)^{B2} * (1-\exp(B3*DBH/top))^{B4}$$

where:

Dinc = diameter increment for period
Tinc = top height increment for period
DBH = initial diameter breast height
top = initial top height of this species
CCF = Crown Competition Factor index
Bi = regression coefficients for each species

	(DBH)/(Top Height)					
CCF	.04	.08	.12	.16	.20	.24
100 Open	0.031	0.086	0.140	0.187	0.224	0.253
200 Dom	0.023	0.064	0.105	0.141	0.169	0.190
300 Cdom	0.020	0.055	0.089	0.119	0.143	0.161
400 Int	0.018	0.049	0.079	0.106	0.127	0.143
500 Sup	0.016	0.044	0.072	0.097	0.116	0.131

Table 5. The diameter increment surface for Douglas-fir in the Pacific Northwest region from SPS.LIB

Data Requirements

The data required to calibrate the DBH increment surface typically comes from remeasured permanent plots. At least two measurements are desirable at an interval where the change in height is greater than 10 feet. The more measurement intervals the better.

The goal is to have a sufficient sample size in each of the "cells" of the above surface—say 30 or more observations for each combination of **CCF** and **DBH/Top Height**. The best possible situation would be to have remeasurement data from permanent plots starting when the trees were breast height through to rotation age, where the plots were managed like the property as a whole. The measurement data from permanent plots should include DBH, live crown ratio, total tree height, and an estimate of site index from appropriate site trees on or near the plot.

Such data is rarely available and would take a long time to obtain. The next best data would be from a series of permanent plots in stands of similar species and site that cover the range of **CCF** and **DBH/Top Height** "cells" in Table 4.

The data would be grouped by **species**, plot **CCF**, and **DBH/Top Height**. The "cell" estimates in Table 4 are calculated as a mean of the data observations that match each "cell." The estimated mean is only as good as the observations from which it is calculated. A sufficient sample size is important, but may not offset poor measurement data. Some "smoothing" is usually required, especially around the edge "cells," and especially in cases where sample sizes are small.

Height Growth In SPS

Description

The tree height increment equation functions in the same manner as the diameter equation:

$$\text{Hinc/Tinc} = B1 + B2 * \{1 - (\text{CCF}/600)^{B3}\} * \text{Rh}$$

where:

$\text{Rh} = (\text{ht/top})B4$ (form 1)

or $\text{Rh} = 1 - [1 - \exp(B4 * \text{ht/top})](B5 * \text{CCF})$ (form 2)

Hinc = tree height increment

	(DBH)/(Top Height)					
CCF	.04	.08	.12	.16	.20	.24
100 Open	0.775	0.837	0.894	0.949	1.000	1.049
200 Dom	0.774	0.837	0.894	0.949	1.000	1.049
300 Cdom	0.772	0.833	0.891	0.945	0.996	1.045
400 Int	0.744	0.804	0.860	0.912	0.961	1.008
500 Sup	0.594	0.642	0.686	0.728	0.767	0.805

Table 6. The height increment surface for Douglas-fir in the Pacific Northwest region from SPS.LIB

Data Requirements

The data required to calibrate the height increment surface typically comes from remeasured permanent plots. At least two measurements are desirable at an interval where the change in height is greater than 10 feet. The more measurement intervals the better.

The goal is to have a sufficient sample size in each of the "cells" of the above surface—say 30 or more observations for each combination of **CCF** and **DBH/Top Height**. The best possible situation would be to have remeasurement data from permanent plots starting when the trees were breast height through to rotation age where the plots were managed like the property as a whole. The measurement data from permanent plots should include DBH, live crown ratio, total tree height, and an estimate of site index from appropriate site trees on or near the plot.

Such data is rarely available and would take a long time to obtain. The next best data would be from a series of permanent plots in stands of similar species and site that cover the range of **CCF** and **DBH/Top Height** "cells. The data would be grouped by **species**, plot **CCF**, and **DBH/Top Height**. The "cell" estimates are calculated as a mean of the data observations that match each "cell." The estimated mean is only as good as observations from which it is calculated. A sufficient sample size is important, but may not offset poor measurement data. Some "smoothing" is usually required, especially around the edge "cells," and especially in cases where sample sizes are small.

Mortality In SPS

Description

Mortality in the stand occurs due to tree size and competition for growing space. The number of trees dying in a given growth period is determined from the following series of equations:

$\text{Dead} = 0.95 * \text{tpai} * \{R * (1-\text{Cm}/\text{CCF})\}$
where
Dead = number of trees per acre dying in the ith diameter class
tpai = number of trees per acre in the ith diameter class
$\text{Cm} = \text{CCF} + B1 * \exp(B2*\text{CCF}/100)$ $(\text{Cm} < B3)$
$R = 1 + (\text{Rsp} - 1) * S$
$S = (\text{CCF}-100)/500$ $(0 < S < 1)$
Rsp = relative tree size and vigor in the stand
$= (\%\text{Cr} - \text{Xc})/\text{SDc} + (\text{DBH} - \text{Xd})/\text{SDd}$ $(0.1 < \text{Rsp} < 4)$
%Cr = percent live crown of total height
Xc = arithmetic mean of %Cr of all trees
Xd = arithmetic mean of DBH of all trees
SDc = standard deviation of %Cr
SDd = standard deviation of DBH

Data Requirements

The probability of tree mortality is generally greatest when trees are young and decreases with age and size. Data for calibrating mortality generally is obtained from records of mortality on permanent plots. The typical permanent plot installed for diameter and height growth is generally too small to get an adequate sample of mortality.

The best possible situation would be to have remeasurement data from permanent plots for major species and site classes. Measurements of mortality should start when the trees are breast height and continue through to rotation age at 5 or 10-year intervals, managing the plots like the stands they represent. Any subset of this information would be useful, and data could be collected simultaneously in different species and size classes for a site class. This would reduce the elapsed data collection time from a rotation to 5 or 10 years if the property contained enough species, site and density classes.

Volumes

The SPS tree volume routine works from DBH, total height, Rh_{80} and the merch top limit as absolute DIB or percent of DBH. The taper functions are used to compute height to the lower of the merch DIB or merch percent of DBH. The volume routine then walks up the stem, in increments of either the fixed log length or the variable lengths called in the woods. At each step, SPS calculates the butt and scaling diameter of the segment using the taper functions and bark ratios. From the log length and diameters SPS can calculate the cubic and Scribner board foot volume for the piece.

If a piece would extend past the merch top height it is truncated at the merch top. If the piece is smaller than the minimum merchantable piece, no board volume is applied and cubic volume goes only to the total stem volume. If the short piece is the only piece in the tree, and a tree must have a full log (#PCS = 1), no merchantable volume is applied.

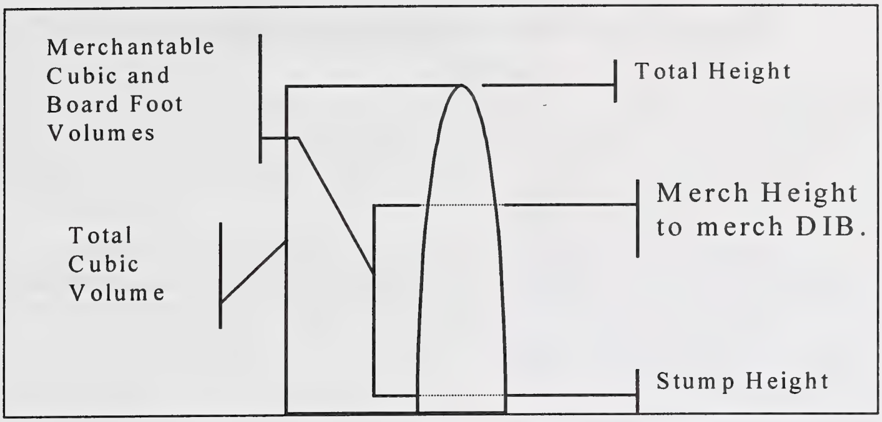
Merchantable Cubic and Board Foot Volumes
Total Height
Merch Height to merch DIB.
Total Cubic Volume
Stump Height

Figure 3. Relationships between volume and heights

Log Volumes

Cubic volumes for individual tree segments (stump, logs and top) are computed as the frustum of a cone:

$$CV = h * 0.005454154 * (d_1^2 + d_1 * d_2 + d_2^2) / 3$$

where:

CV is cubic foot volume
h is the length of the piece in feet
d_1 is DIB in inches at the base of the piece
d_2 is DIB in inches at the top of the piece
0.005454154 is the constant for converting squared diameter in inches to cross sectional area in square feet.

Board foot volumes are determined from the scaling diameter and log length using the Factors for Computing Log Volumes as published by the Columbia River Log Scaling Association. Short-log (east side of the Cascade Range) or long-log (west-side of the Cascade Range) scaling rules can be selected.

Stand Density Management Application

SPS was used to develop target density management curves to maximize cubic foot volume growth and maximize present net value (PNV). Pure Douglas-fir stands were defined at planting and grown in ten-year time steps. Iterations were made in batch mode where trees per acre were reduced by five-tree increments. The results were analyzed at each time step to select the max-growth and max-PNV regimes based on growth in the next time step. Once the max-growth and max-PNV density was determined for a time step, the stand was grown using several five-tree reductions, etc.

The results were generally invariant to site index and presented as trees per acre by diameter at breast height (DBH) and relative density by DBH curves. The implied spacing by DBH was also produced. The max-PNV curve was generally parallel to the max-growth curve, but suggested fewer trees per acre be left.

The curves have been used to locate candidate stands for thinning. Note that if a stand falls below a curve, a spacing thinning may still benefit the stand if it is clumped.

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Stand and Tree Integrated Model (STIM)

Steve Stearns-Smith, RPF[1]

Abstract

The Stand and Tree Integrated Model (STIM) uniquely links a whole-stand model with a non-spatial diameter-class model. Two separate even-age, single-species versions were developed by the Canadian Forest Service in 1996 for coastal western hemlock and trembling aspen. Both are calibrated for natural and thinned stands using permanent sample plot (PSP) databases dominated by 5-15 year remeasurement (growth) data. The models exhibit good predictive capability within this range. Behavior over longer projections has not been validated but yields appear to be biologically reasonable. The minimum size tree accepted by the hemlock model is 5.5m height; for aspen it is 12.0m height and 9.0 cm diameter (BH). Hence, young stand growth is not dynamically modelled for either species. User provided tree list input must meet these minimum sizes, alternatively the model can predict tree lists based on database (PSP) averages from a wide range of user supplied stand-level characteristics. A friendly Windows interface provides a wide range of tabular and graphical output including stand yield tables and diameter distributions. Both models are currently available for downloading at no cost from the BC Forest Service website at:

http://www.for.gov.bc.ca/cgi-shl/research/gy/softreg.exe

Background

The Stand and Tree Integrated Model (STIM) was originally developed by the Canadian Forest Service (Pacific Forestry Centre, Victoria). Two separate even-age, single-species versions were released for coastal western hemlock and trembling aspen in 1996. In 1997, the Canadian Forest Service eliminated their Growth and Yield Program, and custodianship for STIM was transferred to the BC Ministry of Forests.

Model Overview

STIM's model architecture is a unique combination of a whole-stand model linked to a non-spatial diameter-class model. Both models rely on user-provided site index estimates to drive growth rates. The whole-stand model projects per-hectare stand statistics such as volume, stems, and basal area along with average diameter and top-height. The diameter-class model projects tree list data and provides yield data by size class. The diameter-class model can be set to reconcile with the whole-stand model after every growth-step in order to take advantage of the greater long-term stability of the whole-stand model projections. Access to STIM is provided through a user-friendly Windows interface that is both flexible and intuitive.

The hemlock and aspen models were calibrated for natural and thinned stands with large databases from remeasured permanent sample plots (PSPs). Both hemlock and aspen models are calibrated to four separate geographic regions within their respective database ranges. For hemlock these are: coastal Oregon, coastal Washington, the Cascades and coastal BC; and for aspen: Boreal Taiga plains (BC, AB), Boreal plains (SK, MA), Cordillera (BC, AB) and Minnesota. PSP databases for both species are dominated by 5-15 year remeasurement (growth) data. Consequently, the models exhibit good predictive capability for 5-15 year projections. Behavior over longer projections has not been validated but yields appear to be biologically reasonable.

Model Operation and Use

Limitations within the PSP databases restrict application of the hemlock growth models to trees greater than 5.5m height. Similarly, the minimum size aspen tree that can be modelled is 12.0m height and 9.0 cm diameter (breast-height). Hence, young stand growth cannot be dynamically modelled for either species. Breast-height age is used in the hemlock model, while total age is used in the aspen model.

Input options are quite flexible. STIM can generate a yield projection solely from a site index estimate, however the best projection requires input of a detailed tree list from a stand exam. Tree list data must meet or exceed the respective minimum sizes (height and/or diameter) for each species. In the absence of a tree list, the model can predict one by drawing upon database averages. Although site index is the only required input for generating a predicted tree list, accuracy can be enhanced

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significantly by providing additional stand-level data such as top-height, trees per hectare, average diameter, etc.

Tabular model output consists of stand yield tables and projected tree lists. An accompanying graphics program allows graphing of stand yield tables and diameter distributions.

As is typical of all models, the yields derived with STIM may not match operational yields for a number of reasons. Models like STIM predict average yields derived from their calibration databases. Most PSP's, including those used to calibrate STIM, were not located randomly and therefore cannot be viewed as an operational inventory. Stand conditions in PSPs intentionally reflect better than average conditions with respect to pests and disease incidence and stocking uniformity. Even though PSPs include normal endemic pest and disease levels, they don't reflect the same range (including epidemics) found in an operational inventory. This allows modelling to focus on basic biological relationships that are not confounded (and complicated) by external factors. This means it is sometimes necessary, especially in inventory and planning applications, to modify model yields with some type of operational adjustment factors (OAFs). OAFs are necessarily model specific and must account for both landbase factors (e.g., swamps, rock outcrops, roads, landings, etc) and biological factors (e.g., pest, diseases, decay, etc). No specific work has been done on OAFs for STIM. Refer to TIPSY documentation for a more detailed discussion of OAFs.

Stand Density Management and Other Applications

Thinning is the only silvicultural treatment supported by STIM. There are no provisions for fertilization, pruning or any other treatment. Establishment density modelling can only be conducted indirectly due to STIM's minimum tree size limits. The user must first use external information to estimate the stand characteristics at STIM's minimum tree size threshold for a given establishment density.

Thinning can be requested at any time during a growth sequence; multiple thinnings are also possible. However, since thinning is an integral part of the growth model, early thinnings cannot be scheduled before the stand has reached the model's minimum tree size thresholds for height and/or diameter. Thinning specifications are flexible and can be based upon the quantity (absolute or percentage) removed (or residual) expressed as either basal area or trees per hectare. A d/D ratio (dbhg removed / DBHg original) must also be specified. This ratio determines the relative size of the trees to be removed.

The application of any model, including STIM, in silvicultural decision support requires a clear statement of management objectives translated into appropriate quantitative values that can be identified in model output. Care must be taken to understand the implications and limitations of using various quantitative measures as surrogates for various management objectives. Refer to the "Model Comparison and Overview" paper by this author elsewhere in these proceedings for further information.

STIM's input flexibility also facilitates its use in inventory and planning. As with any model, STIM's applicability to a specific inventory depends on the presence of corresponding variables within the inventory. To generate useful projections with STIM for inventory and planning purposes, it is recommended that a minimum of site index, top height and stand density (basal area or trees per hectare) be present in the inventory database.

Conclusions

STIM is a unique model within a user-friendly interface which provides flexibility in both input and thinning prescriptions. However, users may find STIM's limited species and minimum tree size thresholds are the things that most often preclude its use in various situations.

Developing Crop Plans for Alberta Species

Robert J. Day[1]

Introduction

Over the last 50 years, fire protection and harvesting have co-acted to change the "natural" ecology of the forests of Alberta. In the July/August edition of *Canadian Geographic* magazine, Don Gayton pointed out the significant importance of both "high" and "low" intensity fire in both "regenerating" and "thinning" Alberta's lodgepole pine forest (Gayton 1998). Don Gayton says:

> *"The typical post-fire lodgepole stand is an even-age densely stocked monoculture—10,000 stems per hectare is not uncommon. It needs thinning by a light fire in order to grow into a healthy stand of strong trees. Otherwise it will become overly dense, or ingrown, and vulnerable to a hot, stand-replacing wildfire that will spawn yet another ingrown stand."*

Increasingly effective fire protection has very effectively blocked both the reproduction and "natural" thinning of lodgepole pine and almost all other the commercial species, and has created a severe imbalance in the age-class structure of the Alberta forest. Harvesting of the mature and often over-mature merchantable timber that is not replaced by regeneration and sometimes is replaced by weed species particularly blue joint grass (*Calamagrostis canadensis* (Michx.) Nutt.) will eventually lead to timber shortages.

The development of Crop Plans for Alberta species is new. Up to now, and probably for the next 30 years, almost all the timber needed to supply Alberta's forest industries will be harvested from natural fire origin stands that regenerated at ultra-high density. The future harvest will depend on the skill of the foresters responsible for regenerating and tending the *"new"* forest. It is to be hoped that the *"new"* forests will be managed with well designed Crop Plans for the maximum benefit of Albertans.

The development of Crop Plans with or without thinnings is an ancient practice in the silviculture of western European forests and is widely practiced in many parts of the world (Day 1998a). Crop plans for growing and thinning lodgepole pine (*Pinus contorta* Dougl. ex. Loud var. *latifolia* Engelm.) in Great Britain, Finland and Sweden have become of considerable interest as Alberta begins to manage it natural lodgepole pine forests (Hamilton and Christie 1971, Edwards and Christie 1981, Flewelling and Drew 1984). Unfortunately, the Europeans do not grow white or black spruce or aspen poplar, so experience with these species is lacking.

Objectives

The objectives of this paper are to:

1) **Review crop planning** with specific reference to the principal native commercial species in Alberta.
2) **Describe the methods used to develop crop plans for Alberta species** with specific reference to lodgepole pine, black spruce (*Picea mariana* (Mill. B.S.P.), white spruce (*Picea glauca* (Moench) Voss), and trembling aspen (*Populus tremuloides* Michx.).
3) **Propose preliminary crop plans** for: a) lodgepole pine, b) black spruce, c) white spruce and, d) trembling aspen.

Review of Crop Planning

A Crop Plan is a clearly thought out silvicultural plan designed to assist in growing a forest stand or crop at densities that improve or maximize the quantity or value of the timber produced (Day 1985, Day 1998b). A crop plan includes:

1) A **preharvest silvicultural inspection** to assess: a) the **species composition**, b) the **stand structure**, c) the **total volume or basal area**, d) the **mean annual increment** (MAI) of the stand to be harvested (*if any*); and e) the **site quality, site index** or **yield class** for the crop to be grown. In Alberta this inspection would normally takes place in a natural stand slated for felling.
2) A **preharvest silvicultural prescription** for the **species**, and **crop type** to be grown **on a given site** in accordance with a **crop density model**.
3) An estimate of the **maximum volume** or **basal area** per hectare that the species is likely to produce on that site.

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4) A **forecast of the rotation length** and the **expected merchantable yield** of the crop.
5) A **prescription** for the **harvesting method** to be used (if any).
6) An **evaluation** of the **potential slash** that will result from harvesting and a **prescription of slash disposal**.
7) An **evaluation** of the need for, and if needed, **prescription for site preparation**.
8) A **prescription** for the **reproduction method** including the **initial spacing of plantations** or **"spacing" of natural reproduction**.
9) A **prescription** for **weeding the crop**.
10) A **prescription** for **tending**, by **cleaning, pruning, or thinning** the crop.

Crop Plans should be prepared for each of the **Site Types**, and desired **Crop Types** to be grown in any productive commercially managed forest. Normally from five to ten individual crop plans should be sufficient for the management of an industrial or other forest.

The use of well designed **Crop Plans** will provide information on the expected type and quality of wood to be produced from a commercially managed forest.

To make effective **Crop Plans** the silviculturist must know:

1) The **Critical Silvics** of the species to be grown as the forest crops. Critical silvics may be defined as the vital information on the biological behavior of the species that is needed when growing it as a *managed crop*. It will include information on the genetic behavior of the species when it is grown as a crop; the most suitable and dependable reproduction methods; the best site preparation methods for establishing and developing the crop; the seed viability and germination requirements, if it is to be seeded; or stock types to be used when it is planted; the best sowing and planting methods and most suitable sowing or planting periods for the crop species during the growing season; any problems or difficulties in growing the species as a crop (e.g. root deformation of bare root and/or container stock causing lack of stability as the crop develops; insect or disease problems etc.); the need for weed control and release, and other forms of tending such as spacing, cleaning or thinning.
2) The **Desirable Initial Spacing** of each crop species must be determined. This may be the density at which the crop species reaches its the Optimum Rotation (OR) (the rotation of maximum MAI) or the time of the Commercial Rotation (CR) (the rotation of the first commercially feasible harvest). Usually the CR is equal to the OR plus the minimum number of years to reach merchantable diameter. For well managed crops the initial density should usually be set at the density of the first commercial harvest plus an allowance for mortality as defined by the critical silvics of the species. For excessively branchy species, the initial density may have to be set higher than the density of the first commercial harvest to "*train*" the crop (e.g. as in all tolerant hardwoods and branchy conifers such as jack pine [*Pinus banksiana* Lamb.]). Where the initial spacing is to be higher than the density of the crop at the first commercial harvest, the crop will have to be *non-commercially* thinned.
3) The **Length of the Optimum Rotation** (rotation of maximum MAI) so that at the OR the crop may be: a) harvested for pulp, b) allowed to overstock to achieve a higher mean diameter before it is harvested for pulp, or c) thinned to remove pulpwood and allowed to grow further to produce sawlogs or veneer.
4) The **Optimum Densities** that must be maintained by thinning throughout the rotation to maximize production, to increase diameter and shorten the rotation over that occurring in "*natural*" forest stands. Crops managed between 55% and 40% of the densities that occur in "natural" stands are often found to produce considerably larger diameters without loosing either basal area or volume growth.

A **Density Index** is usually defined and applied to ensure that the crop is maintained in an optimum range of number of stems/ha over the entire rotation. The three principal density indices related to the $-^3/_2$ Rule use are:

1) **Spacing Factor% (SF%)** (Brown 1851, Hart 1928, Wilson 1946 and 1979, Bratthe 1957),
2) **Reineke's Stand Density Index (RSDI)** (Reineke 1933),
3) **Volume Stand Density Index (VSDI)** (Harper 1977, Drew and Flewelling 1977, 1978 and 1979, Day 1998b, 1985).

SF%, which was described in 1851 (Brown 1851) is probably the oldest and simplest to use and is recommended for initial Crop Plans in Alberta. SF% is the mean distance between trees in a stand expressed as a percentage of the top height or mean height in m of the 100 largest trees in the stand.

If nothing at all is known about the density requirements of a species, an SF% that ranges around 20% (i.e SF_{max} = 22%, SF_{min} = 18%) is usually recommended (Hummel 1954). As the SF% of many species in "natural" stands is considerably lower, they often range from 9 to 12%, the density is often reduced to 40% of that of natural stands at all stages of growth. For example, when lodgepole pine is grown as a crop in western Europe, it is thinned to maintain it between an upper SF_{max} of 21% (just after thinning) and an SF_{min} of 17% (just before thinning) (Hamilton and Christie 1971, Edwards and Christie 1981).

The RSDI of a stand of trees, which was described by Reineke in 1933, is defined as the number of stems per hectare that occur in the stand when the quadratic mean DBH = 10 cm. RSDI is determined by computing or plotting the regression of $\log_{10}$ number of stems per hectare over $\log_{10}$ quadratic mean DBH in cm.

The VSDI of a stand of trees, which was described by Day in 1985, is defined as the number of stems per hectare that occur in the stand when the volume of the tree of mean volume = 100 dm^3 (or 0.1 m^3). VSDI is determined by computing or plotting the regression of $\log_{10}$ mean stem volume in dm^3 over $\log_{10}$ number of stems per hectare.

In the opinion of the author both RSDI and VSDI are a lot harder to use in field operations and have few of the silvicultural advantages of SF%.

Any of the above density indices *can* be readily determined in "first approximations" by selecting trial stand density index values for each species to be grown from those used for the same or similar species grown as a crop at another location.

In initial Crop Planning work it is *usual* to designate Spacing Factor% values so that the following can be determined:

1) The number of stems/ha to be established so that there are an appropriate number of stems/ha at time of first thinning or harvest.
2) The range of numbers of stems/ha to be maintained by thinning throughout the rotation so that the optimum diameter growth is achieved without loss of production.

By designing well thought out crop plans for each species and site type selected for the production of forest crops, it is possible to reevaluate the productivity of the forest stands supplying any commercial forestry company in terms of their *rate of growth*. Such a reevaluation will of necessity cause the silviculturist to reconsider the current classification of "site types" and will lead to the prioritization of the sites to be utilized for forest crops. Usually only a short exercise in "*crop planning*" will lead to the exclusion of many hectares of forest land currently classified as "*productive*" and to their reclassification as "*unproductive*" for forest crops.

The Yield Class of Alberta Species

One of the best ways of describing the productivity of *stands* of forest species is to define their Yield Class or Mean Annual Increment at their Optimum Rotation. The Yield Classes of natural: a) lodgepole pine, b) black spruce, c) white spruce, and d) trembling aspen forest in Alberta derived from the "Phase 3 Yield Tables" (Alberta 1985) are compared Tables 1 and 2 and Figure 1.

Species and sites with very low productivities should probably be excluded from management or else assigned low silvicultural priorities. For example, if silvicultural investments were only made on land capable of producing MAIs of more than 5.0 m^3/ha (Yield Class 5.0), all species of Site $Index_{50}$ 8 and 12, and in the case of lodgepole pine Site $Index_{50}$ 16, would be excluded from management!

Figure 1 and Table 1 show that "natural" stands of lodgepole pine, black spruce, white spruce, and trembling aspen range in Yield Class from 9.9 m^3/ha/year (Site Index 28 trembling aspen) to 2.3 m^3/ha/year (Site Index 8 black spruce).

Table 2 is of considerable interest to Albertans because it shows that properly managed lodgepole pine in the same Site Index classes grows far more productively in Britain than in *over dense unmanaged* stands in Alberta. As lodgepole pine is mainly grown on poor impeded sites in Scotland and Wales, there is probably room for similar yield improvement in Alberta.

In addition to Yield Class, two of the best measures of dynamic growth are Current Annual Volume Increment (CAI [or PMAI]) or Mean Annual Volume Increment (MAI). The pattern of CAI and MAI growth in volume of even-aged forest crops is characteristic of each crop species and the site(s) on which the crop is grown.

As forest crops planted at optimum density and appropriately thinned often have productivities that increase the Yield Class conservatively by 30 to 40% (Sedjo 1983) or even more over natural stands the advantages of proper stand management are very great indeed.

Figure 2 illustrates the growth pattern of CAI and MAI of "natural" lodgepole pine in Alberta in Yield Classes that range from 3.2 (43) to 8.6 (27) m^3/ha/year (Site $Index_{50}$ classes 12 to 24 m). Figure 3 illustrates the growth pattern of CAI and MAI of natural trembling aspen in Alberta in Yield Classes that range from 5.4 to 9.9 m^3/ha/year (Site $Index_{50}$ classes 16 to 28 m).

A comparison of Figures 2 and 3 shows that: a) Trembling aspen is in a similar series of Yield Classes to lodgepole pine; b) The CAI of natural lodgepole pine rises more rapidly than that of trembling aspen because of its ultra-high initial density; and c) In spite of the very rapid growth of individual aspen stems, the point at which CAI falls below MAI or the "Optimum Biological Rotations" of this species occurs much later than that of lodgepole pine because of its much lower initial density and intolerance.

In theory, a crop grown to the Optimum Biological Rotation would produce the most volume of wood per unit time. The *problem with growing crops on an Optimum Biological Rotation in the north temperate zone is that such rotations are commonly too short to produce stems of commercially useful size*. Thus, the rotation is often extended beyond the Optimum Biological Rotation to a Commercial Rotation that develops an acceptable diameter.

The MAI/ha achieved at an Optimum Biological Rotation describes the productivity of forest stands far better than Site Index Class because it tells to the silviculturist the *rate* of wood volume production and compares the relative rates of production of the various species on the commonly occurring sites. *This point is defined as the Yield Class*.

The general pattern of growth shown in Figures 2 and 3 is typical of *all* even-aged stands, but of course differences in growth occur when the same species is grown over a range of sites, or Site Index classes. For an individual species the shapes of the growth curves on various sites remain much the same, as Figure 4. shows for lodgepole pine.

Although the same general pattern of growth may be constant within a species, it differs markedly between species as shown in Figure 5.

Usually species that regenerate at high density or are fast growing have short Optimum Rotations with steeply ascending and descending MAI/ha growth curves, and slower growing tolerant species have longer Optimum Rotations with slowly ascending and descending MAI/ha curves (Hamilton and Christie 1981). Thus intolerant species with a high demand for soil space, soil water and nutrients often utilise the site less efficiently than the tolerant species and vice versa.

In natural stands in Alberta, black spruce and lodgepole pine grow at ultra-high density causing them to peak in MAI/ha sooner than either trembling aspen which is very intolerant or white spruce which establishes at very low density because of competition with trembling aspen (Figure 5).

In planning crops it is *important to remember that once the CAI/ha has peaked and begins to decline the foliage/ha has begun to decline too*. It is at this time that disease and insect attack may become severe and natural mortality begins in the stand *unless the density of the stand is controlled by thinning* as would be probable in sawlog or veneer crops.

Measures of Stand Density For Use In Crop Plans

The effect of density (number per unit area) on the mean dry weight of plants in competing populations has been shown to obey fundamental laws by the Japanese population biologists Kira *et al.* (1953) and Shinozaki and Kira (1956). These scientists showed that there is a *linear relationship* between the reciprocal of mean plant dry weight ($^1/_w$) and the density (d) of a wide range of plant species. This relationship is the "Reciprocal Yield Law" (Harper 1977) and is expressed as follows:

$$^1/_w = Ad + B \qquad (1)$$

Where:

w = mean plant dry weight,
d = plant density (number/m^2, or number/ha),
A & B = species dependent constants.

The Japanese population biologists also showed that when plant populations are grown at high density mortality causes "*self thinning*" in accordance with the Reciprocal Yield Law (Yoda *et al.* 1973). Yoda's work on self thinning is of *particular importance for forestry* because it shows that when the log of the mean plant dry weight of the survivors in a competing plant population are plotted over the log of their density there is a *linear relationship with a slope of* $-^3/_2$ *or* -1.5 (Equation 2). Thus as the number of plants in any population decreases owing to self thinning, the mean plant dry weight (or volume) of the surviving plants increase. This relationship is defined as the $-{}^{3}/_{2}$ Rule or $-{}^{3}/_{2}$ Power Law.

To demonstrate the *universality of the $-{}^{3}/_{2}$ Power Law for all plants (including trees)*, Harper (Harper 1977, White and Harper 1970) plotted the log of the volume (in cubic feet) of the tree of mean basal area (basal area correlates well with volume) over the log of the number of trees per acre *after thinning* for several coniferous species grown in well managed plantations in Great Britain. The data Harper plotted was taken from the first comprehensive edition of the U.K. "Forest Management Tables" (Bradley *et al.* 1966). Harper plotted the data from Bradley *et al.* (1966) and found that the slope coefficients for the various species ranged from –1.74 to –1.78 instead of the theoretical $-{}^{3}/_{2}$ or –1.5. Had Harper plotted the log of the volume of the tree of mean volume (dm^3) over the log of the number of stems per hectare *just before thinning* when competition is maximal he would have found that the slope coefficients for the British plantation are very much closer to $-{}^{3}/_{2}$ or –1.5 (Table 3). The $-{}^{3}/_{2}$ Power Law was initially expressed by the Japanese ecologists (Yoda *et al.* 1973) as in equation 2. Harper (1977) modified this expression for forest crops as in equation 3:

$$w = Ad^{-b} \tag{2}$$

$$V = k \times N^{-b} \tag{3}$$

Where: w = mean plant dry weight,
V = Volume in m^3 or dm^3 of the tree of mean volume or basal area, or tree of mean basal area in m^2,
d = plant density,
N = Number of stems per hectare.
A = a species dependent y-axis (ordinate) coefficient in equation 2,
k = a species dependent y-axis (ordinate) coefficient in equation 3,
b = the slope coefficient with a theoretical value of $-{}^{3}/_{2}$ or –1.5 for all species.

Crop Plans for Alberta Species

Sample Crop Plans are proposed for growing: a) Yield Class 6.4 (30) Lodgepole Pine, b) Yield Class 5.3 (32) Black Spruce, c) Yield Class 6.1 White Spruce and, d) Yield Class 8.3 (26) Trembling Aspen in Alberta are presented in Tables 4, 5, 6, and 7.

The SF%, RSDI and VSDI graphs for the sample Crop Plans given in Tables 3, 4, 5, and 6 are presented in Figures 6, 7, 8, and 9.

In Figures 6, 7, 8, 9 and 10 the SF% graphs are given at a larger scale than the RSDI or VSDI graphs. SF% is recommended as the principal stand density measure because it is the most practical and versatile for use in field operations and because it almost always predicts RSDI and VSDI accurately. SF% limits are proposed to "control" density, the RSDIs and VSDIs that result from SF% control tend to vary with: a) stand history up to time of measurement, and b) growth response after thinning.

1) **The Line of Limiting Density** (LLD) - These lines were developed by: a) determining the SF%, RSDI and VSDI of all Site Index classes of each species at optimum rotation, b) averaging these values separately.

2) **The Before Thinning Line** - This lines are *often* developed by multiplying the number of stems/ha on the LLD by 0.55. By reducing the LLD to 55% of its number of stems/ha most authorities believe that a properly managed stand will be maintained just outside the "zone of imminent mortality."

   The "before and after thinning" lines presented in this paper are based on careful research and study of: a) the silvics of each species, especially in relation to density; b) the location of the "before and after thinning" lines recommended for individual species (particularly lodgepole pine) or other members of the species genera under management in Europe or elsewhere.

   The SF% values in Table 3a were recommended for the "Management Zone."

   A comparison of Figures 6, 7, 8 and 9 shows that the Alberta species have *widely different tolerances to competition.* Trembling aspen was found to be the most intolerant, white spruce and lodgepole pine were similarly intermediate and black spruce was the most tolerant.

3) **The After Thinning Lines** - These lines were developed by increasing the SF% of the "Before Thinning Line" by 4%. *For example:* As the SF% of lodgepole pine Before Thinning = 17.0%, its SF% After Thinning = 21.0%. In general, 4% increase in SF% tends to result acceptably spaced interventions and in the removal of approximately 33% of the standing basal area or volume. If the amount of basal area or volume removed by

thinning exceeds 33%, SF% values of 3.5% or 3.0% are substituted for 4% to reduce the severity of the thinning.

The following equations were used to construct all the lines on Figures 6 to 9:

1) **Spacing Factor%**
$N = k \times \text{Top Height}^{-2.0}$
or, ${}_{\log}N = k - (2.0 \times {}_{\log}\text{Top Height})$ (4)

2) **RSDI**
$N = k \times \text{DBH}^{-1.561}$
or, $\text{Antilog}({}_{\log}N = k - (1.561 \times {}_{\log}\text{DBH})) = \text{RSDI}$ (5)

3) **VSDI**
$N = k \times \text{Mn. Tree Vol.}^{-0.6667}$
or, $\text{Antilog}({}_{\log}N = k - (0.6667 \times {}_{\log}\text{Mn. Tree Vol})) = \text{VSDI}$ (6)

Discussion

Three functions of the $-^3/_2$ Power Law were examined prior to the development of Crop Plans designed to improve the productivity of Alberta forest. The three functions of the $-^3/_2$ Power Law were the Top Height, DBH and mean tree Volume/number in relation to number of stems/ha on which SF%, RSDI and VSDI are based. The classical principles of density management developed and described by MarMoller (1954), Assmann (1970) and Langsaeter (1941) and others were used to develop Crop Plans based on the lines of limiting density (self-thinning lines) of lodgepole pine, black spruce, white spruce and trembling aspen in natural stands in Alberta (Alberta 1985).

A review of the history and development of the stand density indices commonly used to calculate initial spacing and to control thinning clearly showed that SF% is the best density index for initiating silviculture and management regimes in natural forests. SF% will be the best density index until yield tables and growth models are developed, calibrated and verified for managed stands. Although SF% was selected as the principal density index, both RSDI and VSDI are calculated for each crop plan to provide diagnostic characteristics related to diameter at breast height and volume. By calculating the three density indices separately it is possible diagnose density relations more accurately and while avoiding complex $-^3/_2$ Power Law diagrams that incorporate all three indices, yet depend on the more variable and volume function (Farnden 1996, Smith and Woods 1997) that is harder to measure in the field and compile in the office.

SF% was selected as the primary density index for Alberta species. It was found to correlate well with both RSDI and VSDI in the "Yield tables for unmanaged stands" (Alberta 1985). SF% is also the most practical density index for use in field operations, as it requires only the measurement of top height and number of stems per hectare. The ability of SF% to accurately forecast desired density levels is unaffected by the initial density or history of the stand, making it more effective than either RSDI or VSDI, which can vary greatly between stands with similar SFs.

The SF%s selected in this paper for the principal species in Alberta are derived from their LLDs tempered with consideration of their individual silvics and a comprehensive understanding of the SF%s used to manage them or other members of their genera around the world. The SF%s selected for each species are all close to the standard Spacing Factor of 20% defined by Hummel (1954) and Braathe (1957). The SF%s are as follows for before and after thinning: a) lodgepole pine, 17.0 - 20.0%; b) white spruce, 16.0 - 20.0%; c) black spruce, 16.0 - 18.0%; and d) trembling aspen, 19.5 - 23.5%.

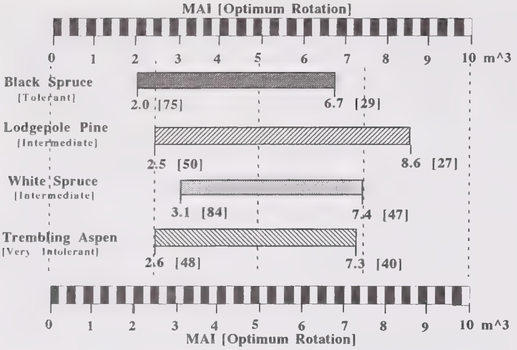


Figure 1. The Yield Classes of natural stands of principal Alberta species after Alberta (1985).

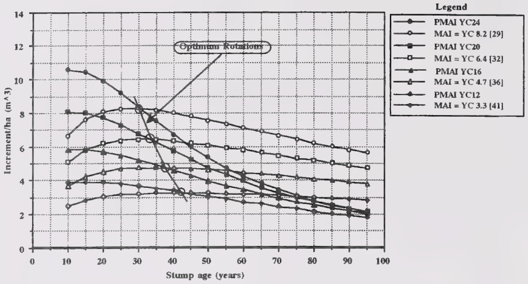


Figure 2. The patterns of CAI and MAI per hectare over age of Yield Class 3.3 to 8.2 m³/ha/year [Site Index$_{50}$ 12 to 24] lodgepole pine in Alberta (after Alberta 1985).

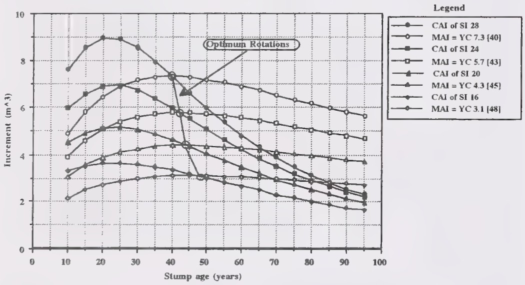


Figure 3. The patterns of CAI and MAI per hectare over age of Yield Class 3.1 to 7.3 [Site Index$_{50}$ 28 to 18] trembling aspen in Alberta (after Alberta 1985).

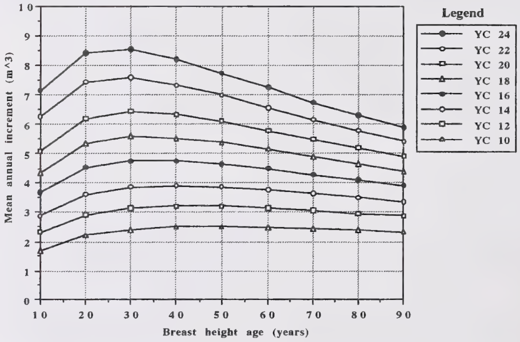
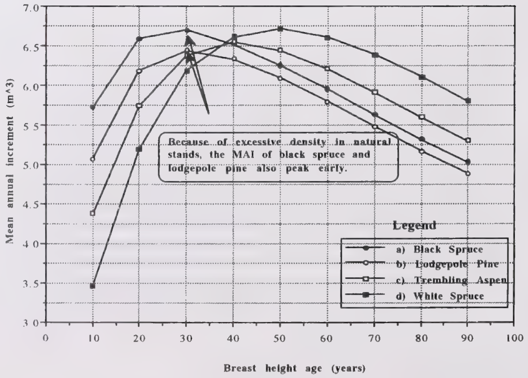
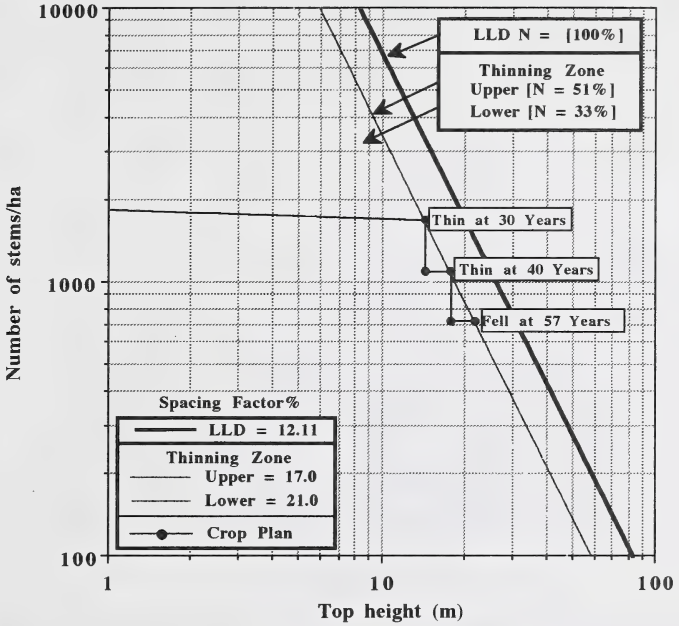


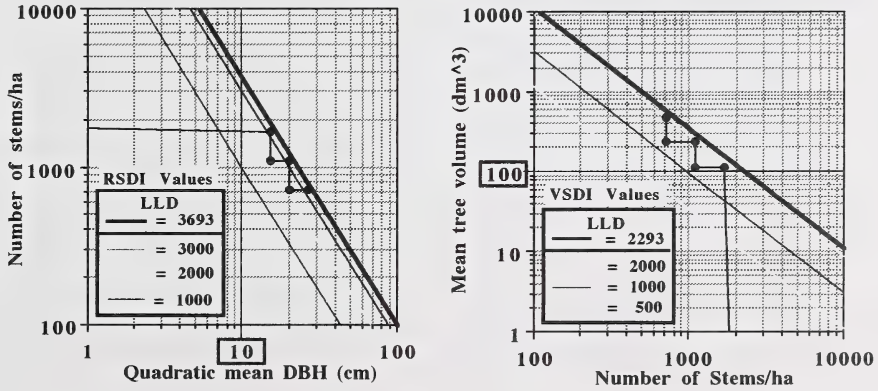
Figure 4. The MAI per hectare over age of unmanaged lodgepole pine in eight Site Index Classes [Yield Classes 24 to 8] in the Alberta (after Alberta 1985).

Figure 5. The MAI per hectare over age of Yield Class 6.5 [approximately]: a) black spruce (very dense and tolerant), b) lodgepole pine (very dense and mid-tolerant), c) trembling aspen (very intolerant and sparse), and white spruce (mid-tolerant and sparse because of aspen competition) in natural stands in Alberta (after Alberta 1985).


Because of excessive density in natural stands, the MAI of black spruce and lodgepole pine also peak early.



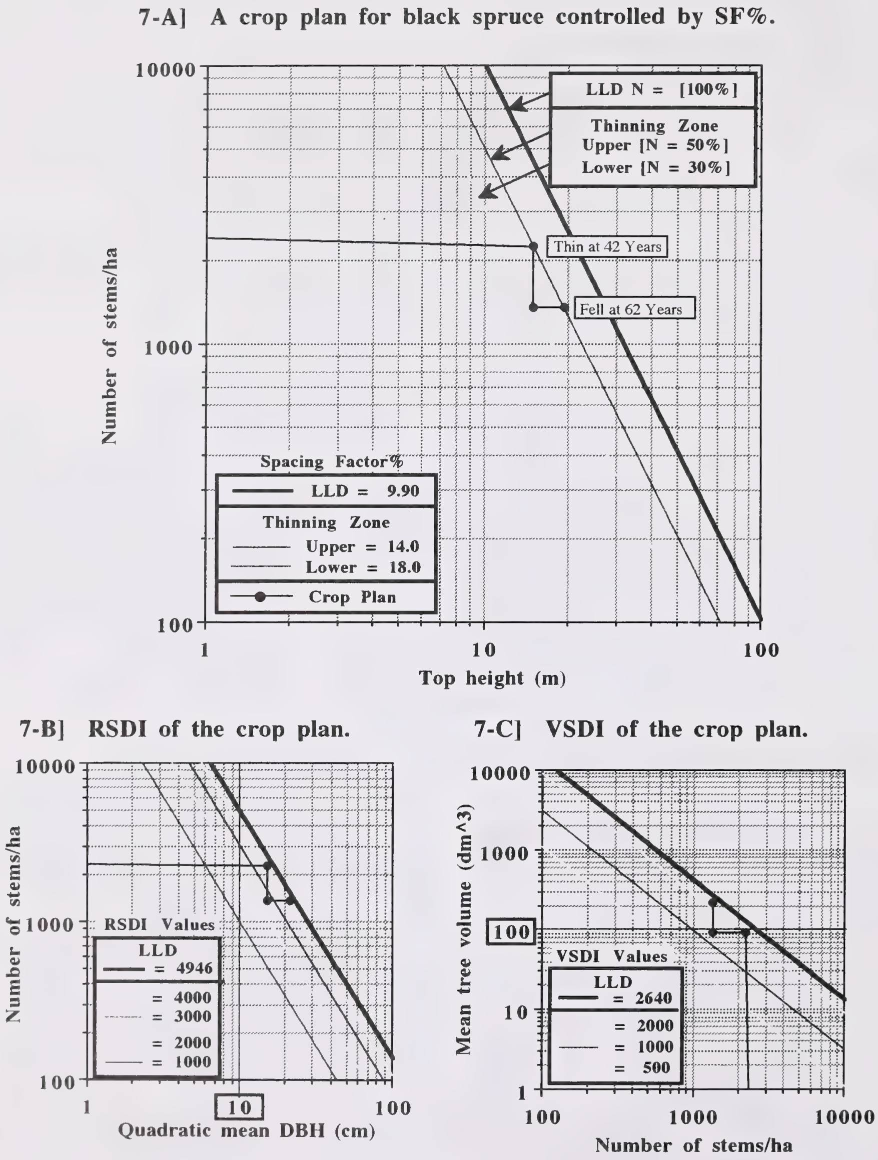
6-A] A crop plan for lodgepole pine controlled by SF%.



6-B] RSDI of the crop plan.

6-C] VSDI of the crop plan.

Figure 6. A Crop Plan proposed for growing Yield Class 6.4 (32) [Site Index 20] Lodgepole Pine in Alberta based on the proposed SPF% values [Upper = 17.0%, Lower = 21.0%].

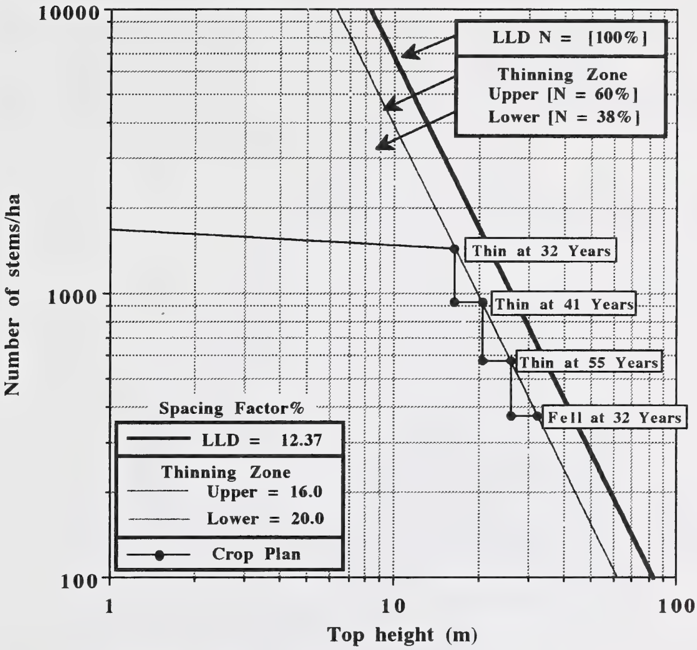


7-A] A crop plan for black spruce controlled by SF%.

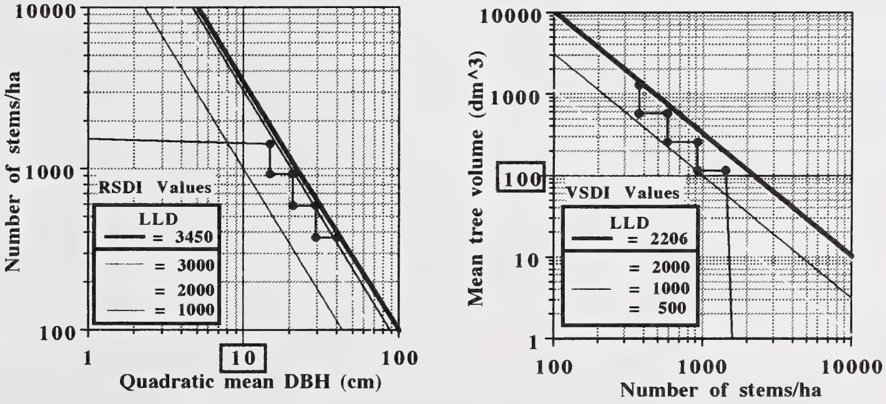
7-B] RSDI of the crop plan.

7-C] VSDI of the crop plan.

Figure 7. A Crop Plan proposed for growing Yield Class 5.3 (32) [Site Index 6] Black Spruce in Alberta based on the proposed SF% values [Upper = 14.0%, Lower = 18.0%].



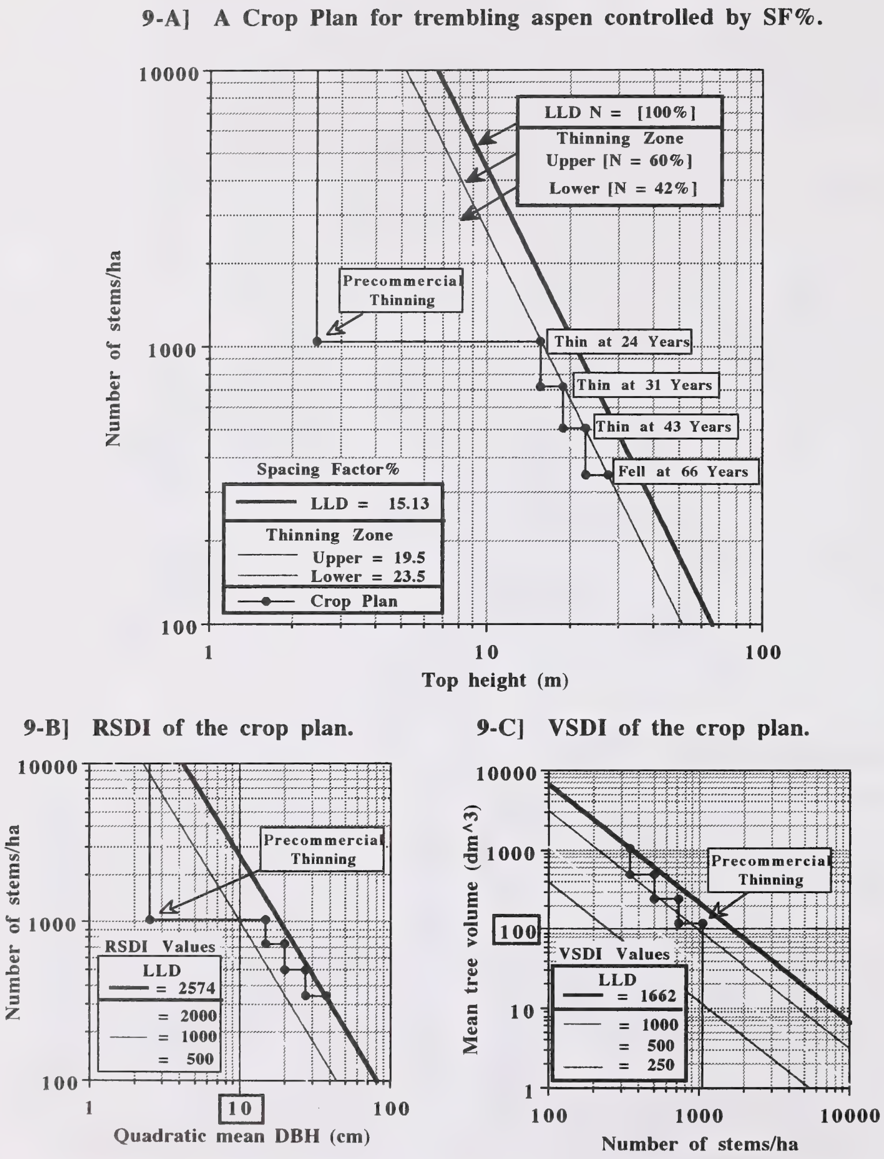
8-A] A crop plan for white spruce controlled by SF%.



8-B] RSDI of the crop plan.

8-C] VSDI of the crop plan.

Figure 8. A Crop Plan for growing Yield Class 6.1 (52) [Site Index 24] White Spruce in Alberta based on the proposed SF% values [Upper = 16.0%, Lower = 20.0%].



9-A] A Crop Plan for trembling aspen controlled by SF%.

9-B] RSDI of the crop plan.

9-C] VSDI of the crop plan.

Figure 9. A Crop Plan proposed for growing Yield Class 8.3 (26) [Site Index 24] Trembling Aspen in Alberta based on the proposed SF% values [Upper = 19.5%, Lower = 23.5%].

Species	**Site Index**				
	28	**24**	**20**	**16**	**12**
Trembling aspen	9.9 [30]	8.4 [32]	6.9 [32]	5.4 [33]	
Lodgepole pine		8.2 [34]	6.4 [37]	4.7 [41]	3.3 [48]
White spruce	7.4 [47]	6.06 [53]	4.8 [63]	3.62 [76]	
Black spruce			7.1 [32]	5.3 [37]	3.7 [44]

Table 1. The Yield Classes [MAI in m³/ha at the Optimum Biological Rotation] and Age [in brackets] of principal Alberta species (after Alberta 1985).

Species	**Site Index**					
	28	**24**	**20**	**16**	**12**	**8**
a) Lodgepole pine in Alta.		8.2 [34]	6.4 [37]	4.7 [41]	3.3 [48]	
b) Lodgepole pine [U.K.] (with spacing and/or thinning)		12.0 [53]	10.0 [51]	8.0 [50]		
Percentage Increase in U.K.		46.0%	56.0%	70.0%		

Table 2. A comparison of the Yield Classes of lodgepole pine in natural stands in Alberta (after Alberta 1985) with lodgepole pine in spaced and thinned stands in the U.K. (after Edwards and Christie 1981).

No.	Species	LLD	Management Zone		Density Tolerance
			Lower	Upper	
1)	Lodgepole Pine	12.1%	17.0%	21.0%	Mid-Tolerant
2)	Black Spruce	9.9%	14.0%	18.0%	Tolerant
3)	White Spruce	12.4%	16.0%	20.0%	Mid-Tolerant
4)	Trembling Aspen	15.1%	19.5%	23.5%	Intolerant

Table 3a. SF% values recommended for the "Management Zone."

Spacing Factors = 17.0% Before Thinning, 21.0% After Thinning [4% Range]

Age	Operation Number	Silvicultural and Harvesting Operations		Stand Characteristics			Top Ht. & Mean Tree Characteristics		
				Number stems/ha	BA/ha (m^2/ha)	Vol/ha (m^3/ha)	Top Ht (m)	DBH (cm)	Vol/ha (dm^3)
-3	1	PHSP/Evaluate Site Index							
-2	2	Harvest Stand							
-1	3	Site Preparation (Where appropriate).							
0	4	Plant 1900 Seedlings/ha (Assuming 80-85% survival to first thinning)							
2	5	Initial Monitoring Survey - Assess need for competition control							
2	6	Competition Control (if necessary)							
4	7	Post-Comp. Control Monitoring - Assess efficacy of treatment							
7	8	Monitoring Survey - Link to establishment (Required)							
12	9	Final Monitoring Survey - Link to Performance							
30	10	1st Thinning	Before	1676	26.76	191.3	14.37	14.26	114.1
30			After	1098	17.53	125.3	14.37	14.26	114.1
40	11	2nd Thinning	Before	1098	34.69	256.6	17.75	20.05	233.7
40			After	719	22.73	168.1	17.75	20.05	233.7
57	12	Final Felling		719	40.41	344.0	21.93	26.74	478.1

Table Continued-

Age	Operation Number	Stand Density Characteristics						Ring Width		MAI
		SI (m)	SF (%)	k	RSDI	k	VSDI	Mean Annual (mm)	Mean Periodic (mm)	(m^3 /ha/yr)
30	10	2.44	17.0	5.0257	2916	4.5960	1831	2.38	2.38	6.38
30		3.02	21.0	4.8421	1910	4.4123	1199	2.38	2.38	
40	11	3.02	17.0	5.0734	3254	4.6198	1934	2.51	2.90	6.41
40		3.73	21.0	4.8898	2132	4.4362	1267	2.51	2.90	
57	12	3.73	17.0	5.0848	3341	4.6435	2042	2.35	1.97	6.04

Summary of Amounts Thinned

Age (Yrs)	BA (m^2/ha)	%BA Standing	Vol (m^3/ha)	%Vol Standing
30	9.23	34.5	65.96	34.5
40	11.96	34.5	88.48	34.5
Tot.	21.19		154.44	

Comparison of Thinnings and Main Crop

BA (m^2/ha)	%BA	Vol (m^3/ha)	%Vol	MAI
Main Crop				
40.41	65.60	344.00	69.02	6.04
Thinnings				
21.19	34.40	154.44	30.98	2.71
Main Crop and Thinnings				
61.60	100.00	498.44	100.00	8.74

Table 3. A Proposed Crop Plan for Yield Class 6.4 [32] Lodgepole Pine with 2 Thinnings

Spacing Factors = 14.0% Before Thinning, 18.0% After Thinning [4% Range]

Age	Operation Number	Silvicultural and Harvesting Operations		Stand Characteristics			Top Ht. & Mean Tree Characteristics		
				Number stems/ha	BA/ha (m^2/ha)	Vol/ha (m^3/ha)	Top Ht (m)	DBH (cm)	Vol/ha (dm^3)
-3	1	PHSP/Evaluate Site Index							
-2	2	Harvest Stand							
-1	3	Site Preparation (Where appropriate).							
0	4	Plant 2500 Seedlings/ha (Assuming 80-85% survival to first thinning)							
2	5	Initial Monitoring Survey - Assess need for competition control							
2	6	Competition Control (if necessary)							
4	7	Post-Comp. Control Monitoring - Assess efficacy of treatment							
7	8	Monitoring Survey - Link to establishment (Required)							
12	9	Final Monitoring Survey - Link to Performance							
42	10	1st Thinning	Before	2229	40.28	205.3	15.13	15.17	92.1
42			After	1348	24.36	124.2	15.13	15.17	92.1
62	11	Final Felling		1348	49.54	290.7	19.45	21.63	215.6

Table Continued-

Age	Operation Number	Stand Density Characteristics						Ring Width		MAI
		SI (m)	SF (%)	k	RSDI	k	VSDI	Mean Annual (mm)	Mean Periodic (mm)	(m^3 /ha/yr)
42	10	2.12	14.0	5.1915	4271	4.6577	2110	1.81	1.81	4.89
42		2.72	18.0	4.9732	2583	4.4394	1276	1.81	1.81	
62	11	2.72	14.0	5.2137	4495	4.6856	2250	1.74	1.62	4.69

Summary of Amounts Thinned

Age (Yrs)	BA (m^2/ha)	%BA Standing	Vol (m^3/ha)	%Vol Standing
42	15.92	39.5	81.12	39.5
Tot.	15.92		81.12	

Comparison of Thinnings and Main Crop

BA (m^2/ha)	%BA	Vol (m^3/ha)	%Vol	MAI
Main Crop				
49.54	75.68	290.70	78.18	4.69
Thinnings				
15.92	24.32	81.12	21.82	1.31

Table 4. A Proposed Crop Plan for Yield Class 5.3 [32] Black Spruce with 1 Thinning

Spacing Factors = 16.0% Before Thinning, 20.0% After Thinning [4% Range]

Age	Operation Number	Silvicultural and Harvesting Operations		Stand Characteristics			Top Ht. & Mean Tree Characteristics		
				Number stems/ha	BA/ha (m^2/ha)	Vol/ha (m^3/ha)	Top Ht (m)	DBH (cm)	Vol/ha (dm^3)
-3	1	PHSP/Evaluate Site Index							
-2	2	Harvest Stand							
-1	3	Site Preparation (Where appropriate).							
0	4	Plant 1800 Seedlings/ha (Assuming 80-85% survival to first thinning)							
2	5	Initial Monitoring Survey - Assess need for competition control							
2	6	Competition Control (if necessary)							
4	7	Post-Comp. Control Monitoring - Assess efficacy of treatment							
7	8	Monitoring Survey - Link to establishment (Required)							
12	9	Final Monitoring Survey - Link to Performance							
32	10	1st Thinning	Before	1443	25.19	167.9	16.45	14.91	116.4
32			After	924	16.13	107.5	16.45	14.91	116.4
41	11	2nd Thinning	Before	924	31.27	236.6	20.56	20.76	256.1
41			After	591	20.02	151.5	20.56	20.76	256.1
55	12	3rd Thinning	Before	591	38.75	333.1	25.69	28.88	563.2
55			After	379	24.81	213.3	25.69	28.88	563.2
81	13	Final Felling		379	47.69	464.5	32.11	40.04	1226.6

Table Continued-

Age	Operation Number	Stand Density Characteristics						Ring Width		MAI
								Mean Annual (mm)	Mean Periodic (mm)	(m^3 /ha/yr)
		SI (m)	SF (%)	k	RSDI	k	VSDI			
32	10	2.63	16.0	4.9910	2691	4.5365	1596	2.33	2.33	5.25
32		3.29	20.0	4.7973	1723	4.3429	1022	2.33	2.33	
41	11	3.29	16.0	5.0217	2889	4.5713	1729	2.53	3.25	5.77
41		4.11	20.0	4.8281	1850	4.3776	1107	2.53	3.25	
55	12	4.11	16.0	5.0519	3097	4.6058	1872	2.63	2.90	6.06
55		5.14	20.0	4.8583	1983	4.4121	1199	2.63	2.90	
81	13	5.14	16.0	5.0798	3302	4.6375	2014	2.47	2.15	5.73

Summary of Amounts Thinned

Age (Yrs)	BA (m^2/ha)	%BA	Vol (m^3/ha)	%Vol
32	9.06	36.0	60.40	36.0
41	11.25	36.0	85.12	36.0
55	13.94	36.0	119.84	36.0
Tot.	34.25		265.36	

Comparison of Thinnings and Main Crop

BA (m^2/ha)	%BA	Vol (m^3/ha)	%Vol	MAI
Main Crop				
47.69	58.20	464.50	63.64	5.73
Thinnings				
34.25	41.80	265.36	36.36	3.28
Main Crop and Thinnings				
81.94	100.00	729.86	100.00	9.01

Table 5. A Proposed Crop Plan for Yield Class 6.1 [52] White Spruce with 3 Thinnings

Spacing Factors = 19.5% Before Thinning, 23.5% After Thinning [4% Range]

Age	Operation Number	Silvicultural and Harvesting Operations		Stand Characteristics			Top Ht. & Mean Tree Characteristics		
				Number stems/ha	BA/ha (m^2/ha)	Vol/ha (m^3/ha)	Top Ht (m)	DBH (cm)	Vol/ha (dm^3)
-1	1	PHSP/Evaluate Site Index							
0	2	Harvest Stand							
2	3	Initial Monitoring Survey - Assess need for competition control							
7	4	Post-Comp. Control Monitoring - Assess efficacy of treatment							
8	5	Monitoring Survey - Link to establishment (Required)							
12	6	Final Monitoring Survey - Link to Performance							
24	7	1st Thinning	Before	1047	18.13	123.7	15.85	14.85	118.1
24			After	721	12.48	85.2	15.85	14.85	118.1
31	8	2nd Thinning	Before	721	22.96	172.0	19.10	20.14	238.6
31			After	496	15.81	118.4	19.10	20.14	238.6
43	9	3rd Thinning	Before	496	29.12	248.9	23.02	27.33	501.6
43			After	342	20.05	171.3	23.02	27.33	501.6
66	10	Final Felling		342	37.42	361.8	27.75	37.34	1059.1

Table Continued-

Age	Operation Number	Stand Density Characteristics						Ring Width		MAI
		SI (m)	SF (%)	k	RSDI	k	VSDI	Mean Annual (mm)	Mean Periodic (mm)	(m^3 /ha/yr)
24	7	3.09	19.5	4.8489	1940	4.4016	1170	3.09	3.09	5.15
24		3.72	23.5	4.6868	1336	4.2395	806	3.09	3.09	
31	8	3.72	19.5	4.8934	2150	4.4430	1287	3.25	3.78	5.55
31		4.49	23.5	4.7312	1480	4.2809	886	3.25	3.78	
43	9	4.49	19.5	4.9383	2384	4.4960	1454	3.18	3.00	5.79
43		5.41	23.5	4.7762	1641	4.3339	1001	3.18	3.00	
66	10	5.41	19.5	4.9878	2671	4.5503	1648	2.83	2.18	5.48

Summary of Amounts Thinned

Age (Yrs)	BA (m^2/ha)	%BA Standing	Vol (m^3/ha)	%Vol Standing
24	5.65	31.2	38.54	31.2
31	7.15	31.2	53.59	31.2
43	9.07	31.2	77.55	31.2
Tot.	21.88		169.68	

Comparison of Thinnings and Main Crop

BA (m^2/ha)	%BA	Vol (m^3/ha)	%Vol	MAI
Main Crop				
37.42	63.11	361.80	68.07	5.48
Thinnings				
21.88	36.89	169.68	31.93	2.57
Main Crop and Thinnings				
59.30	100.00	531.48	100.00	8.05

Table 6. A Proposed Crop Plan for Yield Class 8.3 [26] Tremb. Aspen with 3 Thinnings

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Keys to Determine Optimum Stand Density

J. Klädtke[1]

Introduction

Tools for stand management have been known in Germany since 1800, when Paulsen created the first practicable yield table (Beck 1998). However, since the problems connected with these tools have been known as well, also the wrong tracks followed and errors made are discussed in this paper.

Improving stability and the future assortment structure of the remaining stand, and gaining additional returns from the removals are the main goals of thinnings and important keys for planning tools. Forestry is a long term subject, so that these goals should be brought into a farsighted order. Therefore stability should rank somewhere at the top for safeguarding the basis of production, and additional returns from thinnings should be of minor interest.

As long as the price for timber from thinnings covers the costs, there is no problem since thinnings will be performed.

However, under unfavorable price/cost relations decisions are made very often in a shortsighted way: neglecting the consequences, in order to minimize the costs, thinnings are postponed or avoided.

Farsighted management would perform thinnings in spite of unfavorable market conditions to the profit of stability, growth, and value production of the remaining trees. But it would also try to optimize the relation of input and output.

For this optimization, and therefore a central task for planning tools, the question is how to define the optimal stand density and how to plan the appropriate thinning intensity.

In the following, it will be discussed, if the optimum stand density is equal to

1. maximum stand density
2. maximum volume production
   or rather to
3. maximum value production

Stability - An Important Key To Determine Stand Density

First it has to be explained, why "stability" is emphasized so much. In fact, stability is a central key for a sustainable forestry in Germany and Central Europe, although neglected again and again.

Stability may be defined as the resistance of a tree to biotic and abiotic risks. Among the abiotic risks, wind and snow are the most important. In the long-term average, 20 to 30% of the annual cut are due to windblow, wind break and snow break (Strütt 1991).

A long term statistics of the State forest of Württemberg (Riedl 1978) shows the real distribution of Norway spruce stands differing considerably from the normal forest model, mainly due to damages by snow and wind (Figure 1). According to the normal forest model, the stands were supposed to be distributed evenly by age classes. In reality, there is a surplus in younger and, caused by damages, a deficit in older age classes. Instead of harvesting the stands at the end of rotation, the final cuttings are spread over a wide age range, also taking place in younger stands, still far away from the goal of production.

These older results have been confirmed by an investigation of Strütt (1991), revealing that due to damages in N. spruce and Douglas fir stands the age class of 100 years takes up only 50% in average of the area of the age class of ten years.

According to this investigation, the main factors for the extent of risks are

- stand management
- site condition and tree species combination
- age, respectively height of trees and stands

Although there may be dangers associated with thinnings for 2 to 3 years after the operation, there is no doubt that the stability of trees against biotic and abiotic risks can be definitely improved by an intensive and early initiation of stand management. Many investigations have found that the quotient of height and DBH, the H/D-ratio, is an indicator for the mechanical stability and therefore an appropriate measure for risks due to snow and, somewhat confined, to wind (i.e. Abetz 1976; Kramer 1980; Nielsen 1990).

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H/D-Ratio and Snow Break

Snow break in a Scots pine thinning trial *(Pinus sylvestris)* revealed increasing damages with increasing H/D-ratios (Abetz & Prange 1976). Bent trees occurred at H/D-ratios of more than 120; snow- and crown break at ratios between 94 to 120, where the H/D-ratio of trees with broken crowns was generally lower. Little damage was found for trees with H/D-ratios of 90 and less. For the dominant trees it was evident that the H/D-ratio decreased with increasing thinning intensity.

Similar results were found for N. spruce *(Picea abies)*, where trees with H/D ratio of 80 and less were significantly less affected by snow break than others (Merkel 1975; Johann 1980).

These results have been confirmed by an extensive study of literature concerning snow damages in N. spruce and Scots pine stands by Rottmann (1985).

H/D-Ratio and Wind Break and Wind Blow

Whereas the risks of snow and wind *break* is a question of the breaking strength of a tree and the H/D therefore an appropriate indicator, risks of wind *blow* are first of all a matter of site and tree species combination. However, it has been shown by Nielsen (1990) that spacing and early heavy thinnings lower the H/D-ratios, improve the root system of Norway spruce and stabilize the trees even against wind blow. The importance of early tree number reduction for the stabilization of stands has also been pointed out by many authors from all over Europe (i.e. Horndasch 1971; Mitscherlich 1973; Savill 1983; Rottmann 1986; De Champs 1987). It is also recommended in the Windthrow Handbook for British Columbia Forests, too (Stathers et al. 1994), were critical H/D-ratios for preventing windthrow have been specified.

Optimum Stand Density—Maximum Stand Density?

Although these facts have been known for a long time, the temptation not to thin in order to minimize the costs is very high. But what are the consequences, if the input is set to zero and no thinnings are performed?

Growth

In Figure 2, the tree numbers per ha of an unthinned and a selectively thinned plot of a Norway spruce experiment (N. Spr. 405, Riedlingen) have been plotted against top height. The trial is part of a IUFRO thinning experiment.

Both plots starting with 2500 trees per ha, tree number was reduced step by step in the thinning plot down to 700. The total volume increment of the not thinned plot is superior by 9%, (Table 1). In fact, there are many investigations showing that low or sometimes even no thinnings *may* result in higher total volume production (Schober 1979/80), but it will be shown later on, this has not necessarily to be so.

Assortment and Value Production

More important than simply the scale of total volume production is its distribution on diameter classes. The superiority of the thinned sample plot is evident in Figure 3 and Table 1. Whereas the total volume production of the not thinned plot concentrates on diameters from 16-24 cm, it is between 24 and 34 cm in the thinned plot!

Under the market conditions in Germany, this superiority is equivalent to a much better assortment structure and therefore to a higher value production. From the ecological point of view it is important to mention that the thinned stand is better structurized than the not thinned, since its diameter range is wider. However, supposing better market conditions for small-sized timber it might be possible that a surplus in total volume production does also mean higher net results in the short term. In the long term it has to be asked: How risky is timber production based on maximum stand density?

Stability

In Figure 4, the total volume production of trial N. spruce 405 is plotted against H/D-classes. 99% of the total volume production resulted from trees with H/D ratios of more than 80! Still 84 % of the volume production are allotted on H/D-ratios more than 90. In contrast, 23% of the volume production of the selectively thinned plot fall on H/D ratios more than 80, and only 2.5% on H/D> 90!

In the unthinned stand it is only a matter of time, until its superiority in total volume growth gets lost due to severe damages. The total volume production of dense stands can therefore also be *lower* than that of less dense stands with no mortality, better stability, bigger and more productive crowns and better water and nutrient supply (Johann & Pollanschütz, J. 1974; Burschel, P. 1974).

For an unthinned Douglas fir experimental plot for example, Weise (1995) found 17% of the total volume production allotted to dead or dying trees, damages by snow or wind not included. The living trees turned out to be absolutely inferior to the thinned plots in terms of assortment structure and value production.

Even when maximum stand density strategies may result in higher volume production, it would reduce stability and value production, so that optimum stand density is definitely not equal to maximum stand density.

Optimum Stand Density = Maximum Volume Production?

The necessity of thinnings has been realized by forest practice and science very early, and the multitude of yield tables reflects the different approaches to optimize stand density by stand management.

Many, if not most of these tables, aim at the maximization of volume production, and in the following we will discuss the effects on stability and value production.

One of the best known yield tables in Germany for Norway spruce is the table of Wiedemann (1936/42). The data for this table were derived from stands moderately thinned from below.

In Figure 5, the tree numbers and H/D-ratios of Wiedemann's table are compared to the unthinned plot of the thinning experiment N. spruce 405. Up to a top height of 18 m, the tree numbers of Wiedemann's yield table are extremely high, much higher than that of the unthinned plot.

The H/D-ratio of the experimental plot started with 80 due to the relatively low tree number at 10 m top height. It increases more and more with increasing stand density, but the ratios of Wiedemann's table even exceed these values. Although his data were derived from stands moderately thinned from below, the risks are the same as in the unthinned plot.

Thinning from below is therefore nothing but a compensation of natural mortality, which is not enough to improve the stability of the stand and the growth of the remaining trees.

Scrutinizing the relation between basal area and volume production of many German and European thinning experiments in Norway Spruce and other important tree species, Assmann (1961) found an optimum basal area, where the maximum volume production is reached. This optimum basal area depends on site and stand's age. In younger stands and on better sites, the optimal basal area is below the maximum basal area (Figure 6), which means that these stands need to be thinned in order to maximize the volume increment. In older stands or on poorer sites, the optimum is close or equal to the maximum basal area.

Based on these results, Assmann developed the theory of the critical basal area, defined as the basal area, where at least 95% of the maximum volume increment is reached. Depending on tree species, the critical basal area ranges from 60 to 90% of the maximum basal area. For N. spruce, Assmann also developed a yield table oriented on the critical basal area. (Assmann & Franz 1963/72).

Stability

Calculation of H/D ratios from the data listed in Assmann's yield table for Norway spruce reveals that stand management by the critical basal area theory does not reduce the risk sufficiently (Figure 7). The average H/D-ratios are close to that of the yield table of Wiedemann but with values between 90 and 100 up to 33 m top height are much too high to avoid damage by snow. From this point of view, the insufficiency of many old yield tables mentioned above are valid for tables based on critical basal areas, too.

Growth

The comparison of growth and value production of a long term beech experiment revealed, that the total volume growth is 9% higher on plots keeping the critical basal area than that of the selectively thinned plots (Altherr 1971; Klädtke 1997). But again, the analysis of the diameter structure shows that this advantage is insignificant (Figure 8). As for the remaining stand, the diameter structure of the plots managed according to Assmann's critical basal area theory is rather homogenous, with a maximum between 30 and 38 cm. In contrast, the selectively thinned plots have a clear superiority in the diameter classes higher than 38 cm, and also the diameter structure of the removals is much better. Not presented in the diagram are the advantages for the understory, which is of better vitality in the selectively thinned plots. Especially in beech, these advantages may not be underestimated.

Value Production

In Figure 9, the total net value of the beech experiment for the thinnings, the remaining stand, and the total volume production are presented.

Selective thinning results in higher net incomes from the removal, due to higher thinning volumes and better assortments.

Regarding the remaining stand, the net values of the stands managed by critical basal area exceed that of the selectively thinned, since the volume per ha is higher. But distinguishing between crop trees and other remaining trees, the value of the crop trees of the selectively thinned plots turns out to be convincingly better.

Although these beech stands will have further 30 years to grow, the selectively thinned plots are already superior today in terms of total value production, although minor in volume production. Due to the better diameter growth of the crop trees, this superiority will increase by time more and more.

Optimum Stand Density = Maximum Value Production!!

Summarizing the results, management strategies based on critical basal area as well as on maximum densities may maximize the volume increment, but are detrimental to stability, assortment structure, and value production. The beech experiment shows that only about 45 - 50% of the total volume production falls on marketable assortments. For coniferous tree species this relation is of course better, but as for Norway spruce for example, still 30% of the total harvestable volume production does not cover the costs. These figures underline the decreasing importance of total volume production at least for the situation in Central Europe, and therefore the decreasing importance of classical yield tables, too. Under today's market conditions in Germany, at least 80% of the value production are performed by the future crop trees, so that new decision making tools for stand management are needed, safeguarding stability, maximizing *value* production, and being also applicable for mixed and unevenaged stands.

Stability *plus* Value Production?

Fortunately, stability and value production are no contradiction, but may be combined easily. High stability requires thick and healthy trees, and such trees are generally the most valuable, provided that they are of good quality.

The growth of those trees can be optimized the best by selective thinning strategies, where stand management focuses on the needs of the individual future crop tree.

For an operational planning tool, the definition of production goals is a prerequisite as well as the definition of critical H/D- or crown ratios. Based on these prerequisites, the corresponding thinning intensity has to be derived.

Selection of Future Crop Trees (f.c.t.)

Depending on tree species, 90 (oak) to 250 (N. spruce) trees are selected at top heights between 12 and 17 m, hence quite early (Table 2). For coniferous trees, pruning of the f.c.t. is generally recommended. Due to their comparatively low number, pruning does not take much effort but increases the value of timber production considerably.

Very important for the success of this strategy are the criteria for selection.

1. First of all, f.c.t. must be vital and sound. The vigor of a tree can be estimated easily by its H/D ratio (conifers) , respectively by its crown ratio (deciduous trees), the H/D ratio below 0.8 and the crown ratio at least 0.4. Selecting trees with low vitality, as sometimes done due to quality reasons, is risky, since they may die before reaching the end of rotation.
2. The second important criterion is the stem quality. Unfortunately, the quality of vigorous trees is often quite bad. These trees have to be removed as early as possible.
3. Whereas the criteria 1 and 2 are indispensable, the spatial distribution in the stand is more or less of minor importance. However, selecting f.c.t. standing close together should be avoided, since they would hinder each other with negative consequences for growth and timber quality.

Yield Table for Future Crop Trees

The basics of selective thinning have been understood and applied in forest practice in Baden-Württemberg for decades. Because conventional yield tables were sufficient as planning tools, a yield table for f.t.c. was created in the early 1990s (Klädtke 1993). The model was developed on the example of Norway Spruce, but can be adapted to different tree species too.

This yield table consists of two main components, a growth norm and a thinning model.

The growth norm describes the height growth and the diameter growth of the f.c.t. The height growth, being mainly given by site and age, was simply taken from a conventional yield table describing the height growth more or less sufficiently (Assmann & Franz 1963/72). Diameter growth is mainly dependent on site and growing space and may therefore be defined according to specific targets for stability and production.

Goal of Production

Under German market conditions, the production goal is generally big-sized timber, with diameters at breast height of 50 to 60 cm for N. spruce.

For timber for high quality purposes ring width may be restricted, for example, to maximum 4 mm in the outer part of the stem (Figure 10).

It is clear that in reality the radial increment will vary due to the impact of climatic conditions, but for longer growth periods these effects are supposed to be balanced.

For other purposes radial increment may be not restricted but is expected to run near the maximum potential given by site. In this case the target diameter can be reached in a shorter rotation time.

Stability

In Figure 11, the development of the H/D is plotted against top height. In spite of the restricted radial increment, the H/D ratio stays below .80, in contrast to the corresponding values of Wiedemann's Y.T. for Norway spruce. In the case of accelerated diameter development with wider tree rings, the H/D ratios would be even lower.

Thinning model

Having defined the goals for production and stability, the question is, how to make the trees grow like this. The answer is easy: the tree has to get the growing space corresponding to the aimed diameter increment. To put this into a model, first the radial increment , respectively diameter development was transformed into the crown base development via a DBH-crown width regression.

This relation enables one to calculate for a given diameter the appropriate crown base. For example, based on the target DBH of a f.c.t. at the end of rotation, the corresponding crown base can be derived (Figure 12). The crown base is calculated as a hexagon, since this is easier to handle in modeling.

The crown base of a f.c.t. at the end of rotation is of high importance for the model, because it also allows its application in mixed stands. Assuming *only trees of the same species within this area*, a f.c.t. is exposed to nothing but *intraspecific competition* during its growth, the silvicultural management within this small area being the same as in a pure stand.

In mixed stands, such a "mini" pure stand may be surrounded by other "mini" pure stands of other tree species. *Interspecific competition* occurs only along the border lines. Since the f.c.t. is supposed to be located in the center of the area, its development will not be affected by other tree species, and the regressions needed for the model do not have to consider interspecific relations. This makes it easy to apply the model also in mixed stands.

For the calculation of thinning intensity the crown base *increment* has to be known, which is necessary for the target diameter increment of a f.c.t. within a given planning period, e.g. a decade. This is also the area the f.c.t. has to compete for with surrounding trees, which are going to expand their crowns, too. Therefore, the distance a neighbor tree must keep from the f.c.t. without affecting its crown expansion has to be estimated (Figure 13). This can be done by a linear regression, estimating the DBH of neighbor trees as a function of f.c.t.'s H/D-ratio. From its DBH and the DBH-crown width regression, the distance the neighbor tree has to keep from the f.c.t. can be derived. The area resulting from this distance is the potential range where thinnings are going to take place during the planning period. How many neighbor trees finally have to be removed is calculated by the crown base increment of the f.c.t. and the relation of the potential thinning range to its crown base area:

$$f_{th} = i_{f_{f.c.t.}} \times \left(\frac{p.t.r.}{f_{f.c.t.}} - 1 \right)$$

where

f_{th} : crown base areas of thinning trees [m^2/f.c.t.]

$i_{f_{f.c.t.}}$: crown base area increment of a f.c.t. within a planning period [m^2/f.c.t.]

$f_{f.c.t.}$: crown base of a f.c.t. at the beginning of the planning period [m^2/f.c.t.]

$p.t.r.$: potential thinning range [m^2/f.c.t.]

Simply stated, thinning intensity is given by the target diameter growth of a f.c.t. (= production goal) and its competition: the bigger the target diameter increment and/or the smaller the crown basal area in relation to the potential thinning range, i.e. the higher the competition, the higher the thinning intensity.

For practical application, the result received in square meters crown basal area to be removed per f.c.t. has to be transformed into number and volume of thinning trees.

Calculating the Thinning Operation

In Table 3 the number of trees to be cut around a f.c.t. with a given H-DBH combination is presented.

Input variables are the H-DBH values of individual f.c.t. or mean values of the f.c.t. of a stand.

The higher the H/D-ratio of a f.c.t., the more trees have to be thinned. Trees with H/D-ratios <60 don't have to be released. Between 15 and 17 m, f.c.t. with high H/D-ratios have to be released totally. Thinning intensity decreases with increasing tree height. It is important to mention that the thinning to be performed is a thinning from above, where only competitive neighbor trees have to be cut, the ones hindering the f.c.t. to expand its crown. On average, the DBH of these trees is about 80% of the f.c.t.'s DBH, with positive effects on the assortment structure and the value of the removal.

Another possibility for optimizing the economic results is given by the selection of f.c.t.

In Table 4, the number and H/D ratio per diameter class of 280 f.c.t. in a stand is shown (Columns 1-5). Columns 6 to 9 give information about the removal of the first thinning. The mean H/D-ratio of the f.c.t. is 71 (col. 3), but it ranges from 58 to 88. 28 trees (10%) have an H/D ratio more than 80, 58 trees (21%) of more than 75 (col. 4 and 5). On these 10 , respectively 21% weakest f.c.t. trees, 22 , respectively 40% of the thinning volume are allotted (col. 9). In other words: under bad market conditions for small-sized timber, omitting 10 (20%) of f.c.t. would decrease the thinning volume of non marketable assortments by 20 , respectively 40%. It is decisive from the silvicultural point of view that this would not affect the growth of the remaining f.c.t., or even endanger the stability of the stand.

The silvicultural guidelines of Baden-Württemberg for Norway spruce reflect these findings: they recommend the selection of about 150-250 f.c.t., to be released by removing the biggest 1-3 neighboring trees per thinning. Only trees with at least 70% of the f.c.t.'s DBH are considered to be competitve, smaller trees indifferent. With 1-3 thinning operations per decade, the maximum number of 9 trees to be removed per f.c.t may be only theoretical, but corresponds to the figures in Table 3, allowing the total release of a f.c.t. exposed to high competition.

Summary

Conventional yield tables, often aiming at the maximization of volume increment, are inappropriate planning tools for stand management, since stability and value production are not sufficiently considered.

Based on the concept of selective thinning around future crop trees, a growth model for Norway spruce was developed, guaranteeing stability and optimizing value production. Under consideration of production goals and critical H/D-ratios, the diameter development of a f.c.t. was defined. To achieve the target diameter increment, a thinning model was constructed, where thinning intensity is calculated by the corresponding increment of a f.c.t.'s crown base, and a competition index which is based on its H/D-ratio. Thinning intensity therefore is depending on the target diameter increment of the f.c.t., and the competition. The model is applicable for pure and for mixed stands as well.

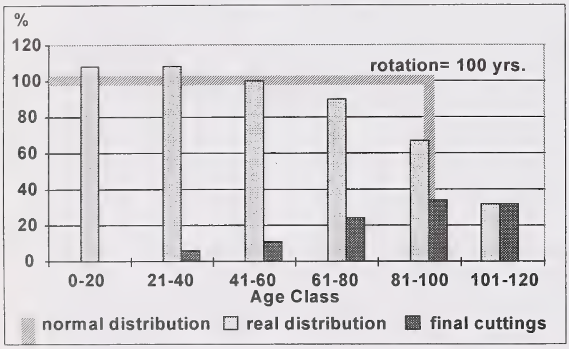


Figure 1: Distribution of N. Spruce Stands by Age Classes, State Forest of Wuerttemberg, 1900-1965 (accord. to Riedl 1978)

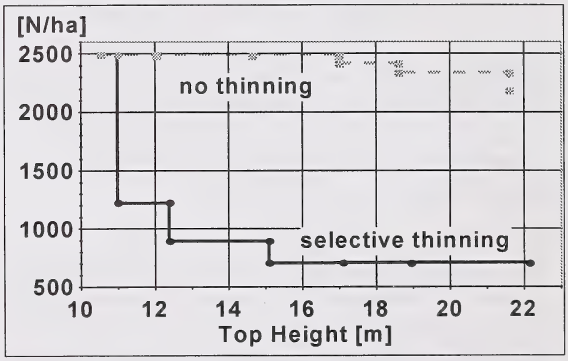


Figure 2: Tree number per hectare versus top height of the not thinned and selectively thinned plot of experiment Norway spruce 405, Riedlingen

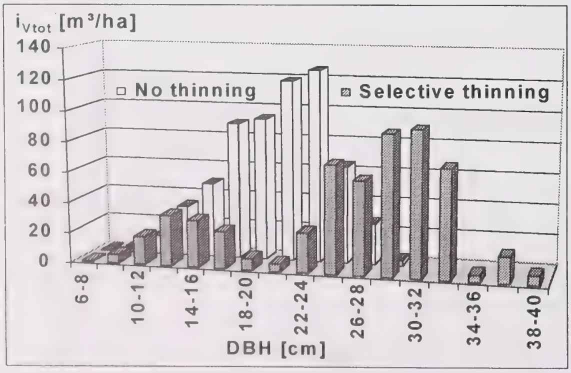


Figure 3: Total volume production per diameter class (Exp. Nw.Sp. 405)

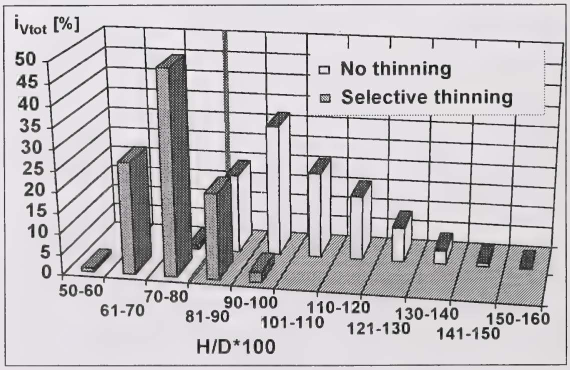


Figure 4: Proportional distribution of the total volume production on H/D-classes

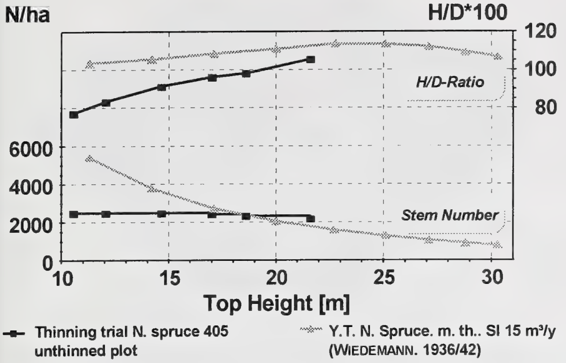


Figure 5: Tree Numbers and H/D-Ratios of Y.T. Wiedemann compared to the not thinned sample plot of experiment N. spruce 405

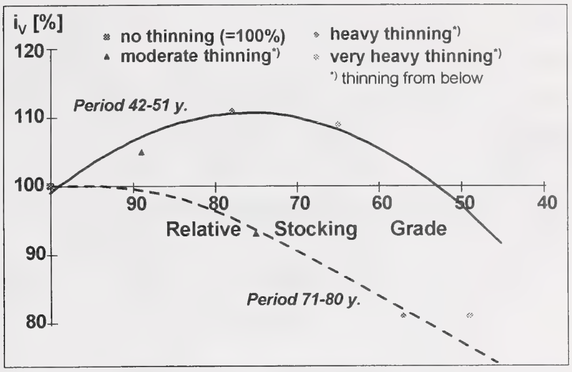


Figure 6: Mean basal area and volume increment (thinning experiment Dalby, [Assmann (1961)]

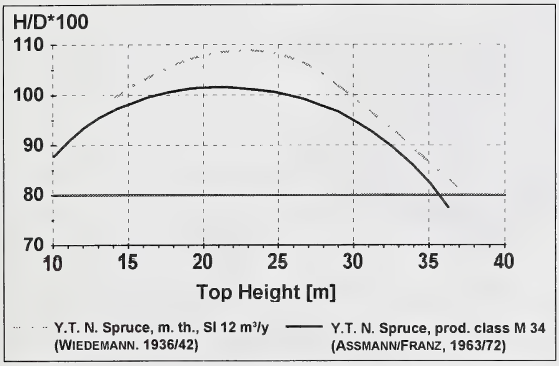


Figure 7: Mean H/D-Ratio of the yield tables for Norway spruce from Assmann/Franz (1963/72) and Wiedemann (1936/42)

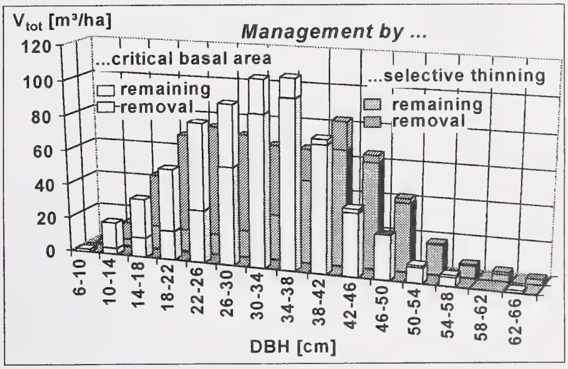


Figure 8: Total volume production of beech per diameter class. Stand management by ...

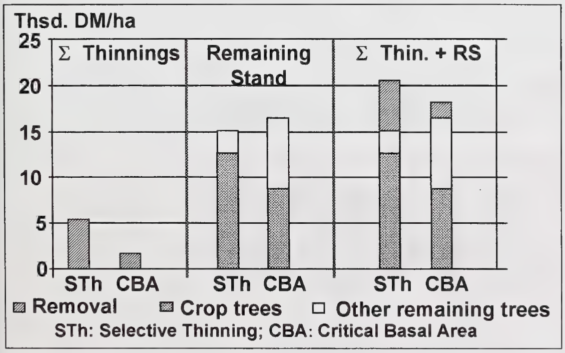


Figure 9: Total net values of beech stands

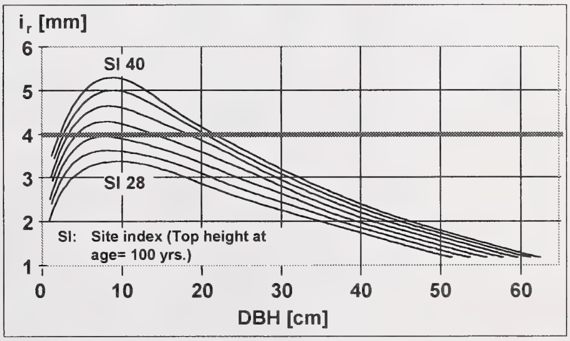


Figure 10: Yield table for Norway spruce: radial increment for high quality timber

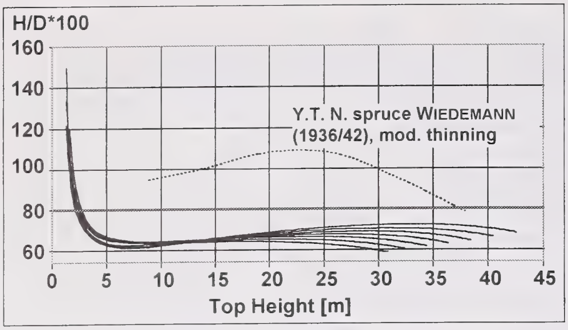


Figure 11: Yield table for Norway spruce: H/D-ratio for high quality timber

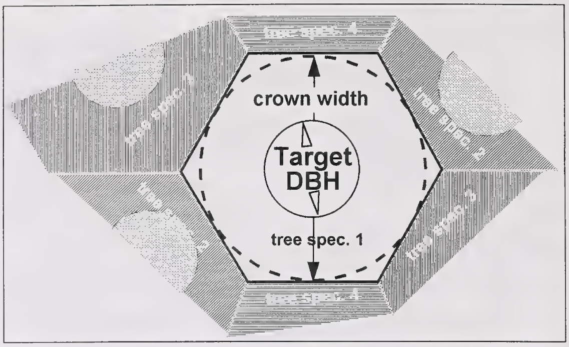
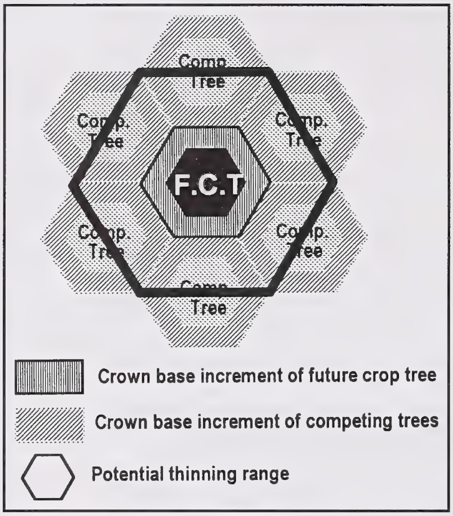


Figure 12: Target diameter, crown base of the f.c.t.(species 1) and crown bases of neighboring f.c.ts (species 2-4) at the end of rotation

Figure 13: Potential thinning range around a f.c.t. within a decade



	Tree number	**Total Volume Production**	**DBH_{mean}**	**DBH_{100}**	**DBH_{max}**
	(N/ha)	(m^3/ha]	[cm]	[cm]	[cm]
not thinned	2180	620	18.8	26.0	39.0
select. thin.	700	569	28.3	33.9	29.0
diff.	+ 1480	+ 51 (+9%)	-9.5	-7.9	-10.0

Table 1: Tree number, total volume production, and diameter at breast height of not thinned and selectively thinned plots of the experiment Norway spruce 405 Riedlingen (values at top height 22 m and age 37)

Tree species	Number of future crop trees	Timing H_{dom} [m]	Pruning up to ... m
Norway spruce	***150 - 250***	***12-15***	***5***
Silver fir	150 - 250	12-15	5
Douglas fir	100 - 200	12-15	10
Scots Pine	200	12-15	5
Beech	100	18	-
Oak	90	17	-

Table 2: Number and timing of selection, respectively, pruning of future crop trees

SI 34	Number of Thinning Trees per Future Crop Tree								
	h_{fct} [m]								
d_{fct} [cm]	15	16	17	18	19	20	21		26
15	8.0	....	....	....	....	....	....		....
16	6.2	6.4	....	....	....	....	....		....
17	4.7	5.0	5.2	....	....	....	....		....
18	3.5	3.9	4.1	4.3	....	....	....		....
19	2.6	2.9	3.2	3.4	3.5	....	....		....
20	1.8	2.2	2.5	2.7	2.8	2.9	....		....
21	1.3	1.6	1.9	2.1	2.2	2.4	2.4		....
22	0.8	1.1	1.4	1.6	1.8	1.9	2.0		....
23	0.5	0.8	1.0	1.2	1.4	1.5	1.6		....
24	0.2	0.5	0.7	0.9	1.0	1.2	1.3		....
25	0	0.3	0.5	0.7	0.8	0.9	1.0		....
26	....	0.1	0.3	0.5	0.6	0.7	0.8		1.0
36	....	....	....	....	....	....	....		....

SI: Site index (Top height at age= 100 yrs.)

d_{fct}: DBH of future crop trees

h_{fct}: Height of future crop trees

▨ H/D- ratio = 100

░ H/D- ratio = 80

▥ H/D- ratio ≤ 60

Table 3: Number of thinning trees per future crop tree

Future Crop Trees					Thinning Trees			
DBH	h	H/D	Number	Σ	Number	Vol.	Vol.	Σ
[cm]	[m]		[N/ha]	%	[N/f.c.t]	[m³/f.c.t.]	[m³/ha]	%
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
15	13.2	88	2	1	6.7	0.90	1.8	2
16	13.4	84	8	4	5.3	0.78	6.2	9
17	13.7	81	18	10	4.0	0.65	11.7	22
18	13.9	77	30	21	3.0	0.53	15.9	40
19	14.2	75	40	35	2.2	0.43	17.2	59
20	14.4	72	45	51	1.6	0.33	14.9	75
21	14.6	70	43	66	1.1	0.25	10.8	87
22	14.8	67	36	79	0.9	0.18	6.5	94
23	15.0	65	26	89	0.5	0.13	3.4	98
24	15.2	63	17	95	0.3	0.08	1.3	99
25	15.4	62	9	98	0.2	0.05	0.5	100
26	15.5	60	4	99	---	---	---	100
27	15.7	58	2	100	---	---	---	100
Ø	Ø	Ø	Σ		Ø	Ø	Σ	
20.6	14.5	71	280		1.7	0.32	90.1	

Table 4: The selection of future crop trees determining thinning intensity

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Nova Scotia Softwood Growth and Yield Model and its Application to Thinning in Red Spruce (*Picea rubens* Sarg.)

Tim McGrath[1]

Introduction

In Nova Scotia much of our silvicultural efforts have concentrated on establishing plantations and pre-commercial thinnings (PCT). Wood supply analyses have shown that these treatments give us the most benefit in terms of sustainable harvest levels. The major result of this program has been to increase the (i) stocking of poorly regenerating stands and (ii) growth rates of our young well stocked stands. By comparison, the amount of commercial thinning (CT) carried out has been modest. Between 1992-1996 an average of approximately 900 hectares of commercial thinning have been performed each year (Figure 1). They have mainly been carried out in previously untreated stands. During this same period, seven times as many hectares have been planted and five times as many pre-commercially thinned.

Our primary objective is still to increase stocking in our forests and to accelerate the growth of our well stocked younger stands. But because of past efforts in these areas, we are now in a position to further increase our wood supply through commercial thinning of these previously spaced or planted stands. Pre-commercially thinned stands are projected (NSDNR, 1993a) to be ready for thinning within 25-30 years of treatment when occurring on average sites (LC=5). Plantations on the other hand, will be eligible for commercial thinning 35-40 years after planting (Table 1).

This means that up to 9,000 hectares of pre-commercial thinnings (established between 1974-78) will approach the appropriate timing for commercial thinning within the next five years. Because of the longer time required for plantations to reach the commercial thinning stage, very few will be ready for this treatment within the same time period.

It is now time to consider the reasons for commercial thinning:

1) Large areas of pre-commercially thinned stands are approaching the time for commercial thinning.
2) Pre-commercial thinnings are more wind-firm and vigorous than untreated stands of the same age making them good candidates for commercial thinning.
3) Mechanical harvesters/processors can perform these treatments in a cost efficient manner.
4) Pre-commercial thinnings are more efficient to commercially thin than unspaced stands due to more uniform piece size and reduced numbers of unmerchantable stems.
5) Stand improvement is possible through species and quality selection at the time of the commercial thinning.
6) Future harvesting carried out in commercially thinned stands can be done more efficiently due to larger piece size.
7) Wood supply can potentially be increased in terms of quantity, size and quality.
8) Wood supply can be obtained earlier and spread out more evenly.
9) Rotation age can be extended while maintaining wood fibre production.
10) Advanced regeneration can be encouraged.

Some possible downsides to this treatment are:

1) More area is required to harvest equal amounts of volume as compared to clearcuts.
2) Roads will have to be maintained for longer periods of time.
3) All the volume in previously pre-commercially thinned stands may be needed to bridge wood supply gaps. Only a forest level wood supply analysis can provide the information required to make this judgement.

The balance of this paper will concentrate on (i) how to determine the timing of commercial thinnings and (ii) the growth and yield outcome of performing commercial thinning at various times, in previously pre-commercially thinned red spruce stands. This will be done using Nova Scotia's Softwood Growth and Yield Model (NSDNR, 1993a).

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Nova Scotia Dept of Natural Resources

When To Commercially Thin?

Full Stocking

Before examining commercial thinning timing, it is important to understand the concept of full stocking. Figure 2 illustrates two different aspects of stocking in a pre-commercially thinned stand. The first relates to how many well spaced trees exist in a stand and the second to what stage of development they are in. For example in a pre-commercially thinned stand spaced to 2.1 metres there will be 2,300 well spaced stems per hectare, when fully stocked, as is illustrated by the left hand part of figure 2. Alternatively, if there are holes in the stand that would be large enough to contain trees at the time the stand is closed in, then the stand will not yield its maximum potential. This is illustrated on the right hand portion of Figure 2 where only 80% of the maximum number of well spaced stems are contained in the stand (1,800stems/ha). By examining the top versus the bottom portion of Figure 2 we can see that the trees in the stands at the top are open grown, while those in the bottom have reached the stage where the crowns are crowded and tree suppression is occurring. The measure of how close a stand is to reaching the closed situation can be expressed as a percentage of a reference line called Stand Density Index (SDI). Stocking in terms of SDI will be discussed in the next section.

The remaining portion of this paper will deal with stands that have no holes in them and therefore represent full stocking or maximum yields, so that focus can be maintained on the relative effect of different thinning timings.

To obtain yields for specific stands the % of the area occupied by well spaced stems can be used to discount the full stocking yields discussed in this paper. For example, if you estimate that only 60% of the stand contains well spaced stems, the full stocking yields should be multiplied by 0.6.

Stand Density Index

Stand Density Index (SDI) estimates are required to determine appropriate thinning times. This relationship is obtained by examining the average stand diameter and number of stems for fully stocked natural stands obtained from Nova Scotia's system of research plots (Figure 3, NSDNR, 1993b). This line represents, for pre-commercial thinnings, the point that natural mortality due to crowding will begin to occur for a given spacing. For example, if 1.8m (6') spacing was used in a pre-commercial thinning, natural mortality will start to occur when the stand has reached an average diameter of approximately 14 cm (6"). Graphically this occurs at the point 3,100 stems/ha intersects with the SDI line. Likewise, if a 2.1m (7') spacing was used (2,300 stems/ha) stand mortality would begin to occur at approximately 17cm (7") in diameter. This relationship is very useful in identifying suitable spacings for given management goals. For example, if a clear-cut harvest was desired when the stand averaged 14cm, 1.8m spacing would be appropriate. But, if a commercial thinning was desired at 14cm, stand suppression would already be occurring, causing an increase in the chances of blowdown and delays in growth response if commercially thinned at this point. A wider spacing, such as 2.1m, would provide the desired 14 cm average diameter before suppression occurred.

Growth & Yield Comparisons of Different Thinning Times

If we plan to commercially thin these pre-commercial thinnings we do not want to wait until suppression occurs, but how much before this point should we thin? Two possible options will be examined with the same common assumptions (Table 2).

The first option would be to commercially thin when the stand has reached 90% of SDI. The second option would involve a commercial thinning at 60% of SDI. According to projections using Nova Scotia's Softwood Growth and Yield (GNY) model (NSDNR, 1993b) the first thinning would occur when the average stand diameter is 13 cm for the 60% case as opposed to 16 cm for the 90% case when performed in a pre-commercially thinned stand spaced to 2.1 m (Figure 4). These projections also show that by thinning at an early stage (60% of SDI) diameter increment is higher at the time of thinning and maintained at a higher level after the thinning as compared to the 90% case. For example, during the 5 year period before the commercial thinning the diameter growth is 40% higher (Figure 5) for the 60% case as opposed to the 90% case (2.0 vs 1.4 cm) and is 30% higher in the 5 year period following the thinning. Despite this, the Mean Annual Increment at the time of the first thinning is 60% higher for the 90% of SDI option. This indicates that higher yields are not necessarily achieved by maximizing tree diameter growth at the commercial thinning stage.

To further explore the differences in yields occurring as a result of different thinning timings, two harvest scenarios were simulated and compared against a "no commercial thinning" or pre-commercial thinning only (PCT) option using the GNY model. The first scenario includes two commercial thinnings performed at 60% of SDI and a final harvest at 90% of SDI. The first commercial thinning is performed at 30 years of age, the second at 40 and the final harvest at 80 years old. The second scenario includes one commercial thinning and a final harvest at 90% of SDI. The thinning occurs at 40 years and the final harvest at 60. The PCT only option involves a final harvest at 45 years. All thinnings are simulated from below and remove 30% of the basal area in the leave strips (Tables 3-4).

Figures 6-10 (following pages), show the (i) standing merchantable volume (stems exceeding 9 cm in diameter), (ii) cumulative harvest amounts (including commercial thinnings), (iii) cumulative mean annual increment (MAI) in merchantable volume harvested per stump height age, (iv) average diameter, and (v) tree size over time for each scenario described in Tables 3 and 4.

The results show that merchantable wood can be obtained earlier in both commercial thinning scenarios. In the case of the 60% scenario merchantable wood is harvested 15 years earlier than the PCT option and 10 years earlier than the 90% scenario (30 vs 40 vs 45 years of age, Figure 7). This first harvest in the 60% scenario, though, will be an expensive one due to small tree size. The average tree will produce only .063 cubic metres of merchantable wood and it will take 16 trees to yield one cubic metre. The yield of this first thinning will be 32 m^3/ha. If the 90% scenario is followed, only slightly less total harvest is achieved by age 40 (69 vs 79 m^3/ha) and the first thinning can be achieved for a lower cost (9 trees/m^3 vs 16). In terms of the total cumulative harvest the 60% scenario results in a mean annual increment of 5.6 m^3/ha, 15% lower than that achieved by the 90% scenario (6.6 m^3/ha). When compared against pre-commercially thinning only, the 60% scenario results in a 7% reduction in merchantable wood production, while the 90% scenario results in a 10% increase over PCT alone. Despite the fact that the total production is lower for the 60% scenario the tree size at the final harvest and at 40 years of age is larger than both the PCT only and 90% scenarios. In fact, the 60% scenario results in an average diameter of 32 cm compared to 24 cm and 18 cm respectively for the 90% and PCT projections at the time of the final harvest.

In summary the 90% scenario results in (Table 5):

1) a lower cost, higher yield initial harvest than the 60% scenario,
2) overall higher yield than the 60% commercial thinning and the pre-commercial thinning only scenarios, and
3) a longer return time between interventions than the 60% scenario, but less than the PCT only.

The 60% scenario results in:

1) a more evenly distributed harvest over time than the other options,
2) earlier initial harvest,
3) slightly higher yield and lower thinning cost by 40 years of age (the second thinning of 60% scenario and the first thinning of the 90% scenario), and
4) a larger piece size and lower harvest cost at final harvest.

Summary

Nova Scotia is well positioned to further boost wood supply through commercial thinning of previously pre-commercially thinned softwood stands. It is important to prescribe pre-commercial thinning with this option in mind, especially regarding early entry into the stands and applying the proper spacing (2.1 to 2.4m). This will result in greater PCT responce and a large enough piece size to make the first commercial thinning economical. The timing of the commercial thinnings is also critical in realizing extra yield. Thinning should be performed at 80-90% of full stocking to avoid (i) stand suppression and mortality if thinned too late and (ii) a loss in yield if thinned too early. It also is stressed that before embarking on a large commercial thinning program that a forest level wood supply should be carried out to see how stand level interventions will affect over-all wood supply.

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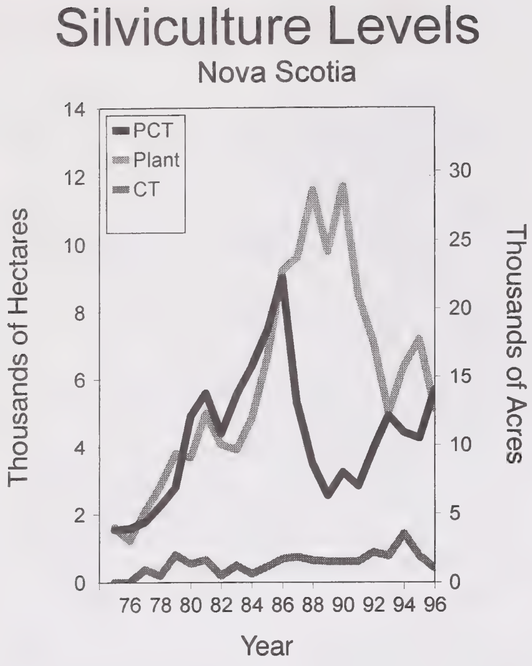

Figure 1

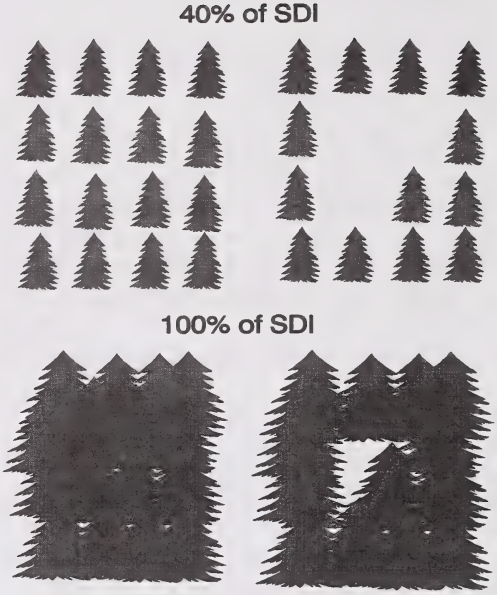

Figure 2

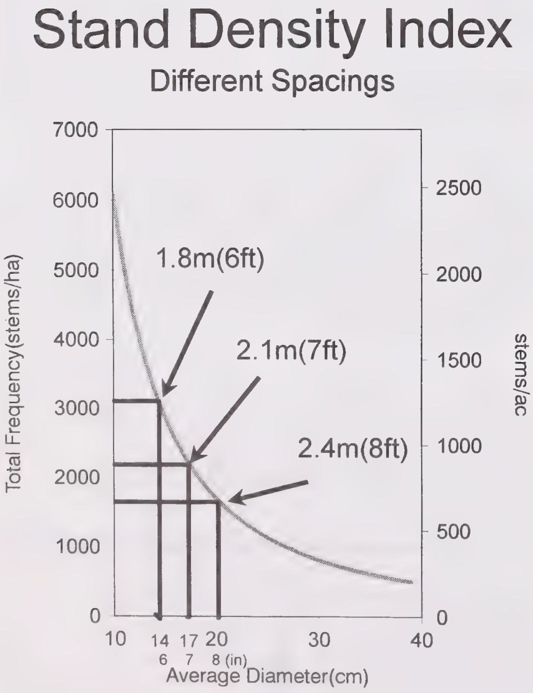

Figure 3

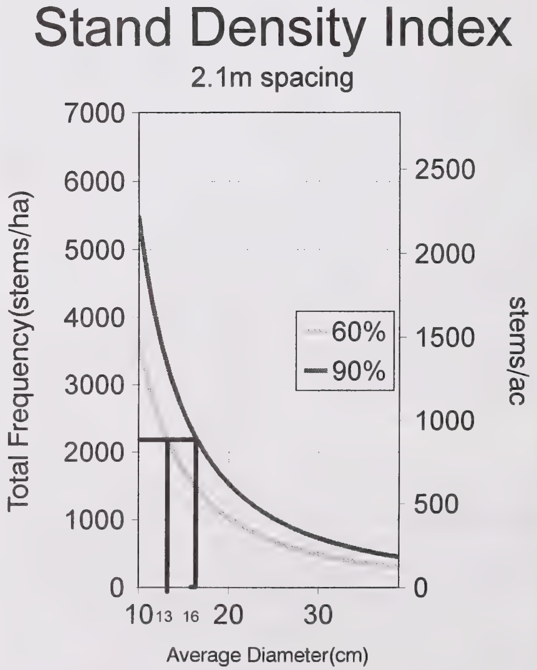

Figure 4

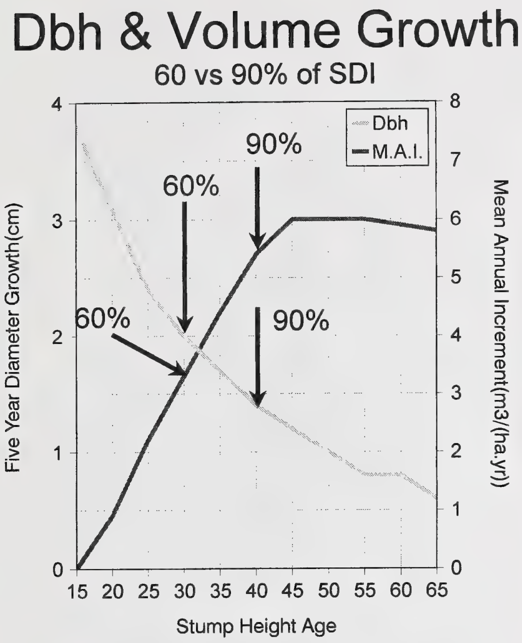

Figure 5

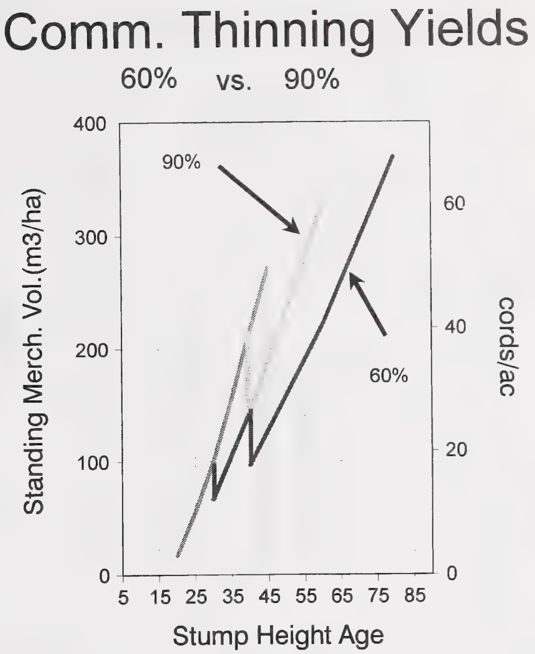

Figure 6

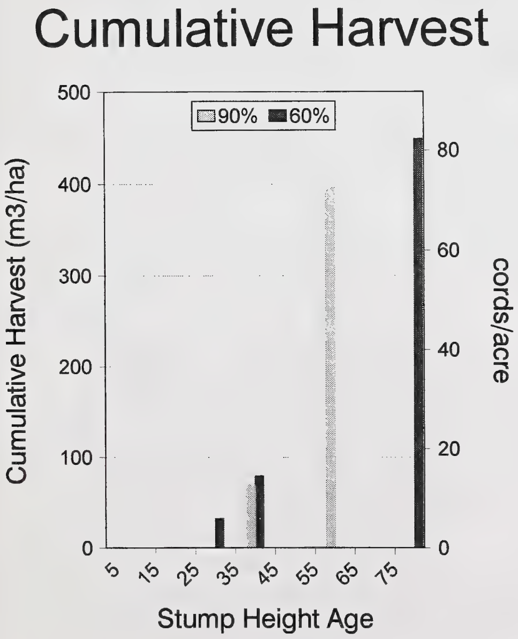

Figure 7

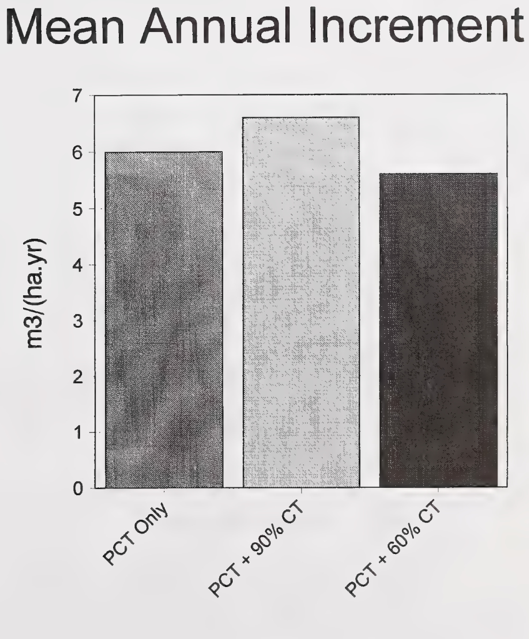

Figure 8

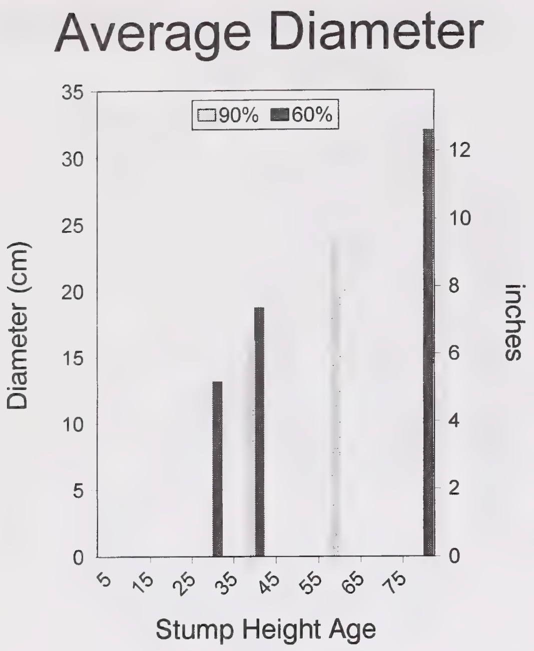

Figure 9

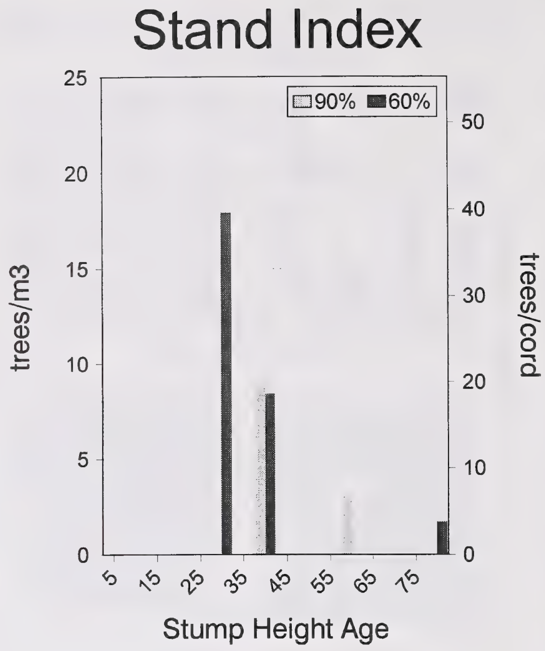

Figure 10

Table 1. Number of years previously treated stand will take to reach the commercial thinning stage[1]

Spacing		Precommercial Thinning[2]	Plantation
Metres	Feet		
1.8 x 1.8	6 x 6	25	35
2.1 x 2.1	7 x 7	27	37
2.4 x 2.4	8 x 8	30	40

[1] LC = 5 m^3/(ha·yr) for Precommercial Thinning and Plantation.
[2] Precommercial Thinning performed when stand is 10 years old (2m in height).

Table 2. Stand Characteristics of Simulated Stand

Species	Red Spruce
Land Capability (LC)	5 m^3/(ha.yr)[a] 0.9 cords/(ac·yr)
Site Index (50)	15.4m 50.5 ft
Age when Precommercially Thinned	10 (stump) 5 (breast)
Precommercial Thinning Spacing	2.1 x 2.1m 7 x 7 ft

[a] For unmanaged fully stocked stand.

Table 3. Characteristics of 60 and 90 % Scenario Simulation.

	60%	90%	PCT
Number of Thinnings	2	1	-
Timing (% of SDI)	60%	90%	-
Age at Thinning	30;40	40	-
Age at Final Harvest	80	60	45

Table 4. Characteristics of Simulated Commercial Thinnings

Basal Area Removal	30%
Selection	From Below
Harvester	Single Grip
Distance Between Trails	20m (66 ft)
Trail Width	3m (10 ft)

Table 5. Comparison of Growth and Yield[1] of Two Different Thinning Timings (60 Versus 90% of SDI).

		60%	90%	PCT
First Commercial Thinning	Age (years)	30	40	-
	Cumulative Harvest in m^3/ha (cds/acre)	32 (6)	69 (13)	-
	Average Merchantable Daimeter in cm (in)	15 (5.9)	18 (6.9)	-
Age 40	Cumulative Harvest in m^3/ha (cds/acre)	79 (14)	69 (13)	-
	Average Merchantable Daimeter in cm (in)	19 (7.4)	18 (6.9)	-
Final Harvest	Age (years)	80	60	45
	Cumulative Harvest in m^3/ha (cds/acre)	449 (82)	396 (73)	272 (50)
	Cumulative Mean Annual Increment in m^3/(ha·yr) (cds/(acre·yr))	5.6 (1.0)	6.6 (1.2)	6.0 (1.1)
	Average Merchantable Diameter in cm (in)	32 (12.6)	24 (9.4)	18 (7.0)

[1] All yields shown in this paper are "full stocking yields". To estimate yields for specific stands these yields should be multiplied by the expected actual stocking at harvest time. For example, if only 80% of the stand is covered by well spaced stems to 2.1 m spacing the final yield for the 60% scenario would be 0.8x459 = 367 m3/ha. All yields shown are merchantable volume of trees exceeding 9cm in diameter to a 7.6 cm diameter top, excluding 15 cm high stumps without deductions for cull and waste.

Model Comparison and Overview

Steve Stearns-Smith, RPF[1]

Abstract

The number of growth and yield models applicable to forests in western Canada is increasing at an unprecedented rate due to recent advances in computing technology. This increase in model diversity is becoming both an boon and a burden to foresters. These technologically advanced tools can help foresters make more informed management decisions, but foresters must first learn to be selective and cautious with these new tools. Each model has a unique approach and niche; no one model is applicable in all situations. In order to obtain the most benefit from these models, foresters have to understand the basic differences among them in order to select the appropriate model for a given situation. Equally important, foresters must understand the unique features of the chosen model in order properly to use it and interpret its output for each specific situation.

Introduction

We are all experiencing an overload of information in all aspects of our lives, not just forestry. Much of the information comes without validation. We trust some sources inherently more than others and we know we cannot possibly check out every piece of information ourselves. Without even thinking about it, we perform *triage* on thousands (maybe billions) of information decisions daily—choosing to look into some things and not others depending on our current needs and attitudes.

The number of growth and yield models applicable to forests in western Canada is increasing at an unprecedented rate due to recent advances in computing technology. The information explosion is clearly affecting our professional lives, as well. Technologically advanced growth and yield tools can help foresters make more informed management decisions, but foresters must first learn to be selective and cautious with these new tools.

Each model has a unique niche; no one model is applicable in all situations. In order to obtain the most benefit from these models, foresters have to understand the basic differences among them in order to select the appropriate model for a given situation. Differences among models stem from differences in the databases used to calibrate them and differences in model architecture. Perfect databases do not exist. Data quality and quantity are always in short supply since funds are limited and long-term growth data requires time.

Likewise, there is no one "best" modelling approach. A model's architecture stems from the modelling approach (philosophy) chosen by the modeller based on the intended application and available data. Limited databases along with our limited knowledge of tree and stand growth necessarily lead to different approaches for different needs and applications. For instance, a primary emphasis on supporting silviculture prescriptions is likely to lead to a different model than an emphasis on inventory or planning. Similarly, an emphasis on single-rotation yields will produce a different model than an emphasis on long-term sustainability. We are already seeing a merging of modelling approaches (e.g., trends toward individual-tree, spatially explicit models) but it will be years before our understanding and data enable us to create one model for all situations and applications. For the immediate future we must expect to deal with more models, not fewer.

Comparing and Selecting Models

Thankfully we don't need to perform integral calculus to understand the basic differences among the various models and make informed decisions regarding their use. First, there are some obvious differences that help us reduce the field of options. Table 1 is a comparison of the models presented at this conference. It list a number of model characteristics and features that may be helpful in selecting an appropriate model for a given situation. Even though there are several models available, it is entirely possible that there may be situations where none of them are appropriate or where even the "best" one should be used with caution.

We each develop our own unique approaches to evaluating various types of information. However, there are a few simple, intuitive things that can help us select growth and yield models. First, keep in mind your intended application, e.g., is it silviculture, inventory or planning? Second, what type of stand do you have and what kind of information do you currently have about it? You can set aside models that are not calibrated for your species and stand types. You can also determine if you currently have sufficient data to run a particular model, as some

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	Prognosis BC	Mixedwood Growth Model (MGM)	Stand Density Mgmt Diagrams (SDMD)	Stand Projection System (SPS)	Stand and Tree Integrated Model (STIM)	Tree and Stand Simulator (TASS)	Table Interpolation Program for Stand Yields (TIPSY)	Silviculture Yields, Lumber Value and Economic Return (SYLVER)
Developer	USFS Intermtn variant adapted to BC by BCFS	Steve Titus, U of Alberta	Multiple authors	Originally Jim Arney (US consultant)	CFS	Ken Mitchell, BCFS	BCFS	BCFS
Distributor and Cost	BCFS (free)	U of Alberta free (web)	BCFS (free, web), OMNR (free), others see literature	Mason, Bruce & Girard Inc. US$75	BCFS (free, web)	not distrib. BCFS does free runs	BCFS (free, web)	not distrib. BCFS does free runs
Model Type	Individual tree, distance independent	Individual tree, distance independent	whole stand	Individual tree, distance independent	whole stand and diameter class	Individual tree, distance dependent	see TASS	TASS BUCK, SAWSIM, GRADE, FAN$Y
Tree Input Data	Tree list	Tree list or stand description	see outputs	Tree list or stand description	Tree list or stand description	Estab. density & spatial dist.	Estab. density	see TASS
Site Productivity Input	Not SI, uses BC BEC and physiography	Site Index (SI)	SI for Top Ht	SI	SI	SI	SI	see TASS
Species	Pw, Lw, Fd, Bg, Hw, Cw, Pl, Se, Py, Hm	Sw, At, Pl, (Sb)	BC (all TIPSY); OMNR Pj, Pr, Pw, Sb	Sw, Sb, Lw, etc	Hwc, At	Fdc, Fdi, Hwc, Hwi, Ss, Bg, Cw, Pl, Sw	Fdc, Fdi, Hwc, Hwi, Ss, Bg, Cw, Pl, Sw	see TASS
Stand Types	single and mixed-spp, even and uneven aged	mixedwood, even and uneven aged	single-spp, even aged	single and mixed-spp, even aged	single-spp, even aged	single-spp, even aged	single-spp, even aged (multi-spp area prorated)	see TASS
Post-estab. activities supported	PCT, partial cutting	PCT, partial cutting	exploration tool	PCT, partial cutting, fertilization	PCT, partial cutting	PCT, partial cutting, fertilization, pruning	PCT	see TASS
Other growth modifiers	root disease					OAFs, some pests and diseases	OAFs, lodgepole repression	see TASS
Output besides yield tables	projected tree lists, diameter distributions	projected tree lists, crop plans	no yield tables, only variables are: Trees/ha, ave tree vol, ave diameter, top ht	projected tree lists, economic analysis	diameter distributions	stand and tree visualization, wood characteristics, projected tree lists, etc	diameter distribution, lumber and logs, mortality and snags, economic analysis	see TASS, plus economic analysis
Development Data Sources	USFS CFI and EP plus PSP from BC S. Interior	Alberta PSP	TIPSY in BC, PSP & TSP elsewhere	tech bulletins and pubs	PSP & EP. Hwc BC, WA, OR; At Canada	PSP & EP. BC, AB, WA, OR	see TASS	see TASS
Unique Features & Applications	partial cutting in complex stands; pest and habitat models available	boreal mixedwood Requires EXCEL 97	simplified one page exploration tool, OMNR software	linked into SIS software, batch I/O	unique dual model architecture	Spatially explicit; crown based custom runs on request	yields from TASS economic analysis	Economic analysis based on lumber value

Abbreviations: BCFS=BC Forest Service; USFS=US Forest Service; OMNR=Ontario Min of Nat Res; CFS=Cdn Forest Service; PCT=precomm thinning; EP=experimental plots; PSP=permanent sample plots; TSP=temporary sample plots; CFI=continuous forest inventory require more detailed data than others (e.g., stand exam data vs. inventory data).

Although all the models in the table have some capability for stand density management, most only support a limited number of options. Model selection will depend what type of density management treatment(s) you are interested in and how much treatment flexibility you require.

Finally, you will no doubt be exposed to conflicting opinions regarding these and other growth and yield models. This is no different than any other situation where people develop different opinions based upon different degrees of understanding and experience. Some differences are due to the models themselves but others stem from differing emphases on volume versus economics, or different interpretations of the historic theory and science behind stand density management. Agreement with actual data should always be the ultimate test for both scientific theories and models—"In God we trust; all others bring data."

Forestry and statistically-based biological experimentation are both relatively new sciences whose joint development is governed largely by the (slow) rate of tree growth. Seeming contradictions among the limited existing experiments serve to highlight our imperfect understanding of complex biological systems and discourage risk-laden investment decisions based on limited (or select) information. Decision making given imperfect information requires risk analyses which take into account the uncertainties regarding future biological and economic consequences. Models can be important tools, but we should not rely solely on them for making decisions.

Model Application and Use

Selecting a model is only half the battle. Proper use of a model also depends on proper selection and preparation of the input data and proper interpretation of the model output. This is why most regulatory agencies avoid any open or implied sanctioning of specific models in favor of yield table approvals. This would be like building inspectors approving a new house solely because it was built with a government sanctioned hammer.

The application of any model in silvicultural decision support also requires a clear statement of management objectives translated into appropriate quantitative values that can be identified in model output. Care must be taken to understand the implications and limitations of using various quantitative measures as surrogates for various management objectives.

For instance, the common use of average diameter as a surrogate for piece size is easily misinterpreted when exploring thinning response. The immediate shift in diameter distribution (and average diameter) due to the thinning operation itself (alias "the chain-saw effect") confounds later interpretations of average diameter and thinning response. Thinning from below immediately narrows the diameter distribution and increases the average diameter. This in turn exaggerates the effect of thinning on the time required to reach a certain piece-size.

Examining the largest diameter classes via stand and stock tables provides a clearer picture of thinning response than average diameter does. The series of graphs in this paper illustrate this concept using a precommercial thinning example in lodgepole pine based on TIPSY output.

Figure 1 illustrates a common interpretation using average diameter as a surrogate for piece size. In this case, it appears that pre-commercial thinning cuts the rotation to a 20cm piece size in half, i.e., 60 versus 120 years.

Figure 2 illustrates the so-called "chain-saw effect" on average diameter at the time of thinning.

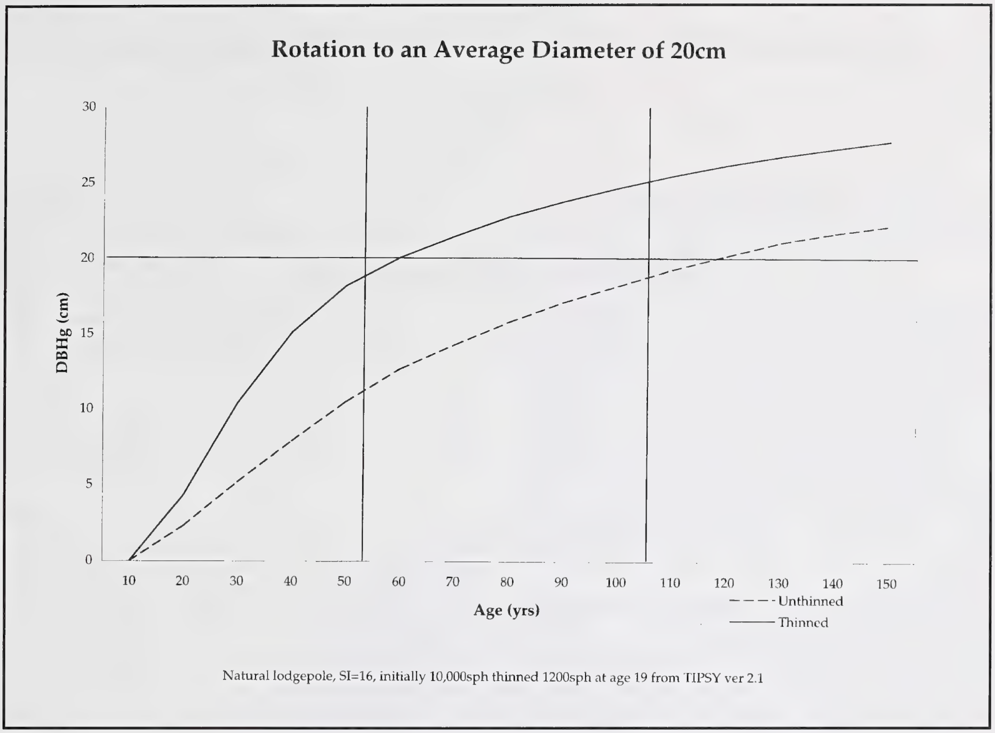
Figure 3 shows the thinned and unthinned diameter distributions at age 60. Note the number of small trees unique to the thinned stand. Examining the unthinned diameter distribution at 80 years (Figure 3) reveals it takes only 20 additional years for the unthinned stand to produce roughly the same number of large trees produced by the thinned stand at 60 years. Whereas reliance on average stand diameter alone would suggest delaying harvest an additional 60 years (Figure 1).

Clearly, average stand diameter exaggerates the effect of thinning on rotation length to a given piece size.

Conclusions

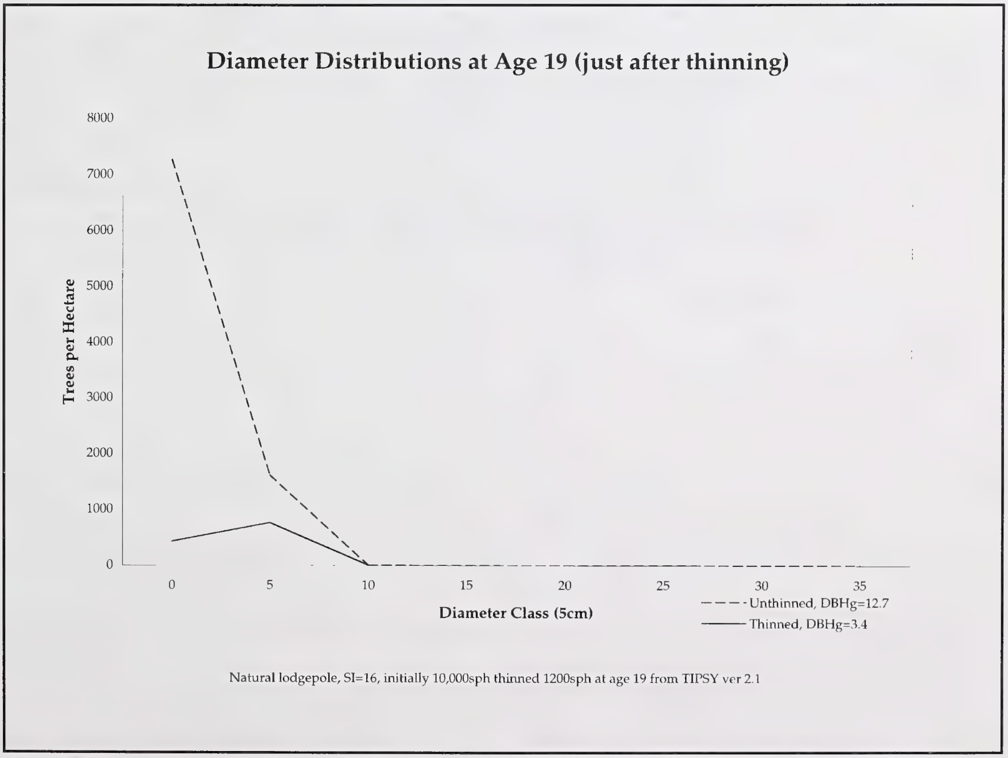
The number of growth and yield models applicable to stand density management in western Canada will continue to increase due to advances in computing technology. Foresters need to become familiar with the general characteristics of all the available models in order to select the appropriate model for any given situation.

After selecting a model, an understanding of model requirements and a quantitative expression of management objectives are needed to properly apply the model and interpret its output. Management decisions should not rely solely on growth and yield models; professional judgment is also required to integrate and risk manage the information from these models and all other sources.


Rotation to an Average Diameter of 20cm

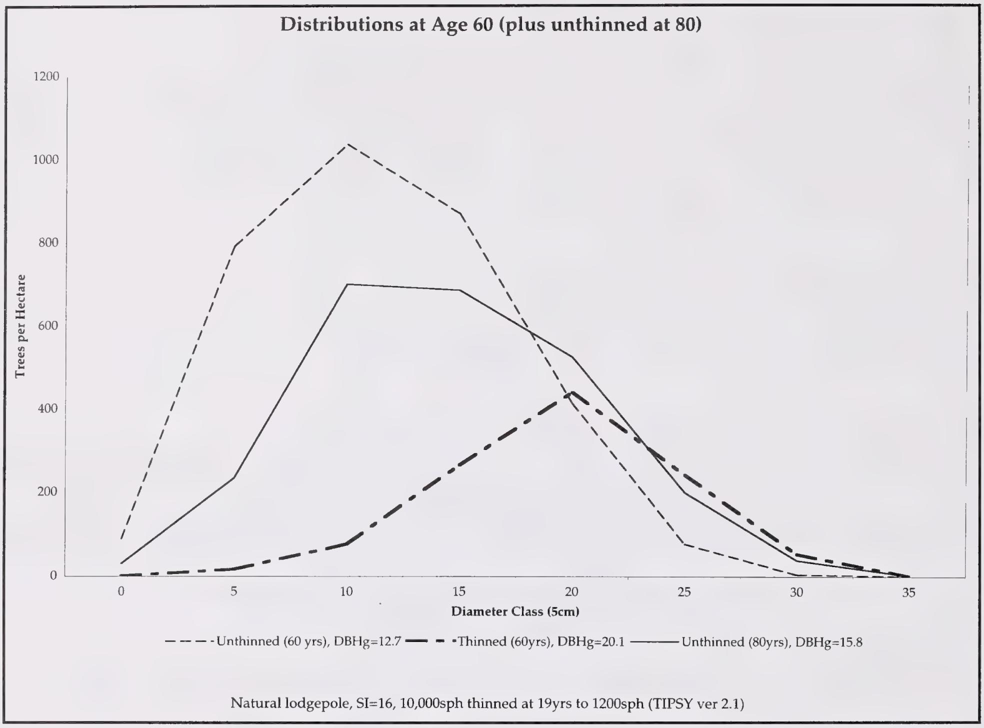
Natural lodgepole, SI=16, initially 10,000sph thinned 1200sph at age 19 from TIPSY ver 2.1

Figure 1. Rotation to an average diameter target of 20cm


Diameter Distributions at Age 19 (just after thinning)

Natural lodgepole, SI=16, initially 10,000sph thinned 1200sph at age 19 from TIPSY ver 2.1

Figure 2. Diameter distributions at age 19 (just after thinning)



Distributions at Age 60 (plus unthinned at 80)

Natural lodgepole, SI=16, 10,000sph thinned at 19yrs to 1200sph (TIPSY ver 2.1)

Figure 3. Diameter distributions at age 60 (plus unthinned at 80)

Forest-Level Effects of Stand Density Treatments[1]

Jordan S. Tanz, RPF[2, 3]

Key ideas

1. Timber supply is driven and controlled by much more than stand growth.
2. Stand treatments affect timber supply through specific, understandable mechanisms.
3. For stand treatments to have a recognized effect on forest-level values, they must be incorporated into a forest-level analysis.
4. Planning silviculture activities should not be based on stand-level objectives alone.

Outline

I will start by explaining some fundamental concepts and terms so that we are all speaking the same language. These include timber supply and related ideas and terms. Then we'll examine timber supply analysis, and the data used in timber supply analysis, particularly the data relevant to discussions about stand density management. Finally, we'll examine the mechanisms by which stand density management activities can affect estimates of timber supply—the link between forest-level and stand-level planning. At the end, I will touch on the framework for silviculture strategy planning that my business partners and I have developed over the last few years.

Concepts

What is timber supply?

Let's start with a simple definition of timber supply: *Timber supply is the rate at which timber becomes available for harvesting*. Timber supply is not the same as timber inventory. Inventory is a stock, measured in cubic meters. Supply is a flow or rate, measured in cubic meters per year. The rate of harvest draws on the standing timber volume, which is replenished by growth.

This definition could be extended to: *Timber supply is the rate at which timber is made available for harvesting in response to social, economic, and environmental considerations*. Timber supply is the portion of the inventory that we make available for harvesting.

We make timber available according to social, economic, and environmental considerations. Social considerations include management objectives for non-timber values and issues such as community stability. Economic considerations, such as prices for wood products, affect utilization standards and the amount of available timber that can be profitably harvested. Environmental considerations include such things as riparian buffers and seral stage structure.

Elements of a timber supply forecast

Timber supply forecasts project the evolution of the forest over the planning horizon of interest, often two to three rotations. They typically show three phases: an initial harvest level (often the current allowable annual cut, or AAC), a long-term harvest level (LTHL), and a transition from the initial harvest level to the LTHL (Figure 1).

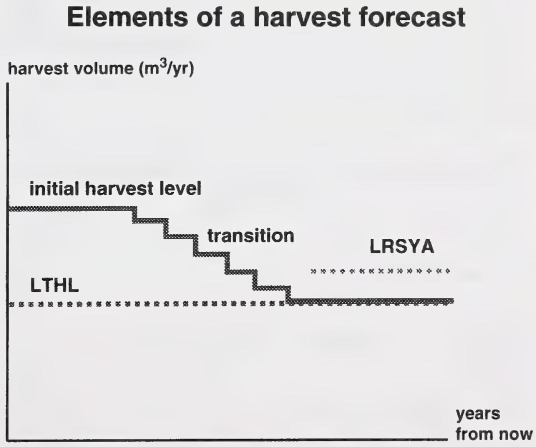


Figure 1. Elements of a typical forecast.

The long-run sustained yield average (LRSYA), is defined in the Alberta Land and Forest Service (ALFS) planning manual as, "the hypothetical timber harvest that can be maintained indefinitely ... once all stands have been converted to a managed state under a specific set of management activities."

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[1] Most of the slides used in the presentation are available on Cortex's web site. http://www.cortex.org

[2] Cortex Consultants Inc., Suite 3A, 1218 Langley Street, Victoria, BC, Canada V8W 1W2

[3] Some of the concepts and graphics presented here have been drawn from earlier papers and presentations developed by Cortex staff, mainly Cortex (1997), Tanz (1995), Williams (1994), and Williams (1998).

We can calculate LRSYA by multiplying the area of each component of our forest (e.g. yield class or analysis unit) by the mean annual increment (MAI) associated with the expected harvest age (e.g. culmination age) for managed stands. LRSYA is the theoretical maximum biological production capacity of the forest landbase, assuming that every stand is cut exactly at the specified rotation age and no constraints affect harvest levels. I say theoretical, because in practice we do not cut stands exactly at the prescribed rotation age, and we do have constraints. But LRSYA does serve as a useful benchmark.

The long-term harvest level, or LTHL as I refer to it, is the level of sustainable harvest found through modeling the evolution of the forest. It is the harvest level that can be sustained indefinitely given a particular forest management strategy, stand management regimes, and estimates of timber growth and yield. It is less than the LRSYA because of management constraints and sub-optimal scheduling.

Timber supply forecasts

The long term is the period that begins when the harvest reaches its sustainable LTHL, usually when harvesting is mainly from managed stands. This does not mean that no old growth remains in the forest, just that the harvest comes almost entirely from managed stands. The short term is the period beginning now, and during which the scheduled harvest levels (AAC) are significantly different than the LTHL. The mid term begins with the end of the short term (often the second decade) and ends when old growth is no longer a significant part of the harvest (Figure 2).

Timber supply forecasts—high timber inventories

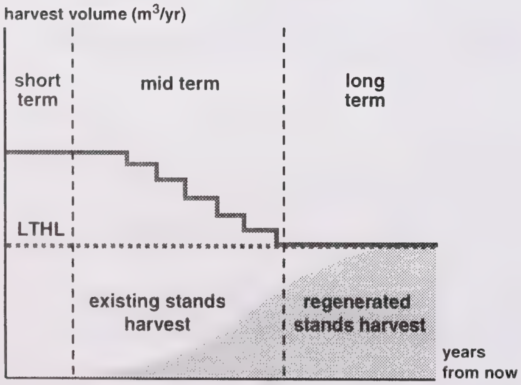

Figure 2. A typical forecast when there is a surplus of available mature timber.

The situation shown here, where current harvest levels are higher than the LTHL, is possible only if there is a large stock of mature standing timber available for harvesting.

A different, but complementary view of the planning horizon is that the long term is when supply is determined by forest growth and management objectives, medium term is when supply is determined by interaction of available inventory and timing of availability of second growth, and short term is determined by the available inventory and decisions about transition strategy.

We say that there is a *surplus of timber* in existing stands when lands allocated to timber production can provide more harvest volume from existing stands than is needed to maintain the harvest at the LTHL (Figure 2).

The situation shown in Figure 3, where current harvest levels are less than the LTHL, is due to a *deficit* or *scarcity of mature timber.*

Timber supply forecasts—low timber inventories

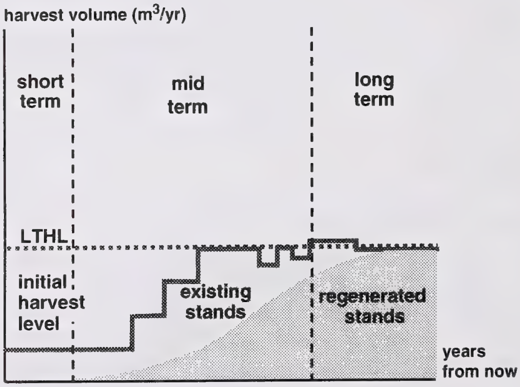

Figure 3. A scarcity of mature timber available for harvesting.

What are the key influences on timber supply?

The key influences on timber supply are environmental values, social values, and economic values (Fig. 4).

In this context, we can restate the definition of timber supply: the flow of timber is driven by economic forces, shaped by social and environmental values, and limited by productive capacity of the forest.

Determinants of timber supply

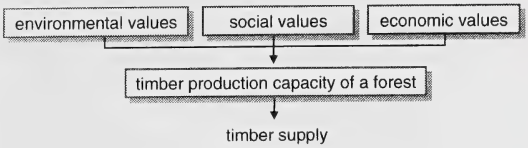

Figure 4. The key influences on timber supply: environmental, social, and economic values.

Alternative pathways to the LTHL

It is important to understand that the shape of the harvest forecast is *chosen*. It is controlled through policy. An example of a harvest policy is:

In the first two decades maintain the current harvest at the highest possible level, thereafter increasing or declining to LRSYA, *without varying between decades by more than 12% per decade.*

Note that this is an example, not legislation or firm policy.

The harvest forecast is not a technical attribute of a forest, it is a decision-maker's choice. There are many possible pathways for transition to the long-term harvest level. The four forecasts shown in Figure 5 are all technically (physically/biologically) feasible. All four begin at the same initial cut level, and all end at the same LTHL. Choosing one over another is a matter of policy.

Alternative pathways to the LTHL

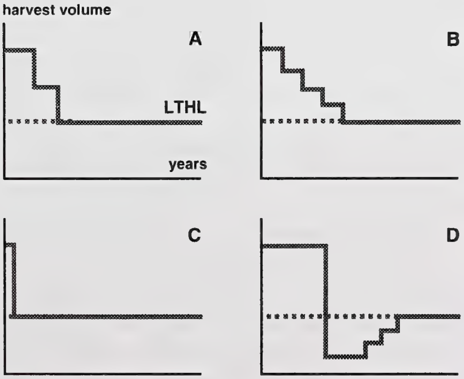

Figure 5. The shape of a harvest forecast is chosen.

Scenario A maintains the current AAC for two decades, followed by two relatively large decreases to the LTHL. Scenario B reduces the AAC in a series of smaller steps down to the LTHL. Scenario C shows an immediate drop to the LTHL. In scenario D, the current harvest level is maintained as long as possible, but eventually has to make a precipitous drop to a level below LTHL, from which it can only increase up to the LTHL when second growth stands reach minimum harvest age.

In evaluating these alternatives, the forest manager must consider biological, economic, and social objectives. Scenarios A and B would both likely be acceptable to the Chief Forester or CEO of a woods operation supporting a large mill in a small community. It is unlikely that the people in that community would be pleased with scenario C or D.

The point is that these are choices, not technical decisions.

How do we arrive at such a schedule?

If we were to log every stand at culmination age, and apply no flow constraints, the resulting "pure" timber supply for a forest might look something like Figure 6, in which the schedule of harvests varies greatly from decade to decade.

Case study forest—unconstrained harvest schedule

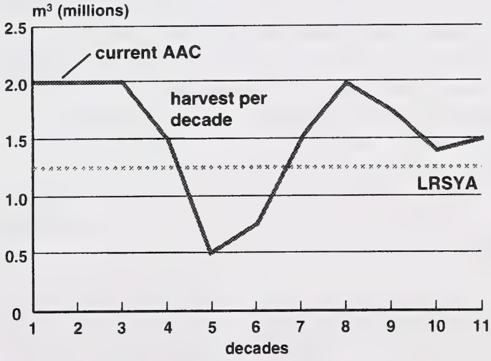

Figure 6. An unconstrained harvest schedule.

In real life, the fluctuations of such a schedule are undesirable. Constraints are used to smooth the flow of volume to make it less variable. As shown by the arrows in Figure 7, some stands that would have been logged in decade 3 are instead held longer to help make up the shortfall in decades 5 and 6. Other stands that would have been logged in decades 8 and 9, are instead harvested early to help make up the shortfall.

The supply forecast resulting from applying flow constraints is shown in Figure 7 as the constrained harvest schedule. By the way, the shape of this forecast is very typical of many forecasts for Timber Supply Areas (TSAs) in British Columbia.

Case study forest—constrained harvest schedule

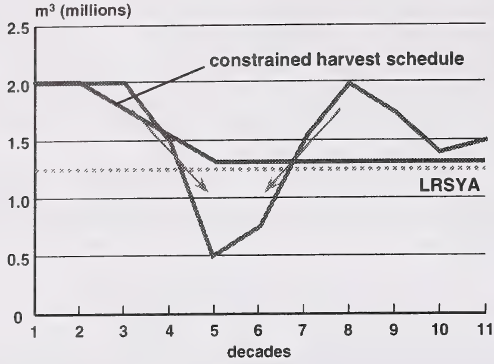

Figure 7. Flow constraints temper harvest-level fluctuations.

Analysis

What is timber supply analysis?

Timber supply analysis is a process of exploring the timber supply effects of alternative forest management strategies and timber harvesting levels. We undertake timber supply analysis with what might be called a forest modeling system. Figure 8 is meant to represent the process described in the Alberta Land and Forest Service (ALFS) Interim Forest Planning Manual.

Forest modeling system

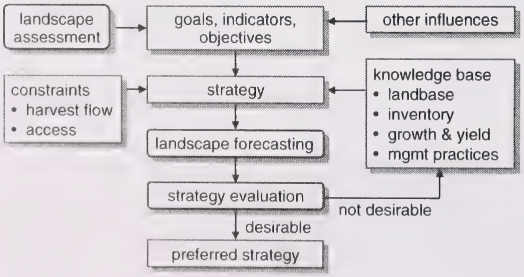

Figure 8. A forest modeling system that meets the requirements of the ALFS Interim Forest Planning Manual.

At the top, we have goals, indicators, and objectives that define the future forest we are trying to create. They are determined through a process called Landscape Assessment, which is the planning manual process aimed at evaluating biological, economic, and social needs for a management unit to ensure that forest management activities do not "unduly impact" opportunities to utilize or access other values. Goals define the desired future forest in broad terms; indicators are the criteria for evaluating progress toward a goal; and objectives are clear, quantitative statements of expected results—specific levels of indicators.

There may be other influences that affect our vision for the future forest. For example, some management decisions, including the management objectives for the forest, are made elsewhere (e.g. legislation, Canadian Council of Forest Ministers, Canadian Standards Association sustainability criteria and indicators).

A strategy is formulated to create the forest defined by the specified goals, objectives, and indicators. Typically, these include harvest schedule options such as order and timing of harvest, silvicultural inputs, forest health, and protection. Next, in a process known as landscape forecasting, the evolution of the forest is projected into the future using information in a knowledge base and projection rules embedded in the model. Indicators of the state of the forest are produced (e.g. age-class distribution) and used in a strategy evaluation. A preferred strategy is chosen, or a new strategy is formulated, forecast, and evaluated.

Landscape forecasting is done with a forest planning model. Strategy evaluation is based on an evaluation of indicators.

Today, we usually use computerized models of timber supply to approximate the effects of various policy and management "levers" on a simulated forest. Such levers could include harvest level, timing of harvest, and amount of planting or other treatments we might undertake. The model forecasts the future values of key indicators such as total growing stock inventory and the harvestable component of growing stock inventory (Figure 9). The average age at which stands are harvested is another useful indicator (Figure 10). Notice that once the original legacy of existing timber has been harvested, the average harvest age stabilizes. In this figure the harvest forecast has been overlaid to show the relationship between harvest flow and average age of harvest—the decade in which the rate of harvest can be increased (decade 7 in this example) depends on when second growth reaches minimum harvest age.

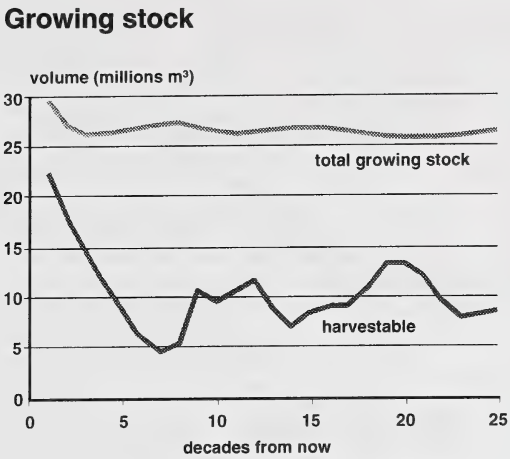

Figure 9. Growing stock inventory indicators.

Data

Our knowledge base for timber supply modeling can be divided into four categories of information: landbase, growth and yield, management practices, and forest inventory.

Landbase Determination

Identifying the timber harvesting landbase is the "netting down" process that reduces the landbase to the parts that will be available for harvesting. The following list shows the types of areas that are excluded from timber harvesting:

- non-productive land
- inoperable areas
- incompatible/single use
- environmentally sensitive areas
- not satisfactorily restocked areas
- unmerchantable stand types
- roads and landings
- riparian buffers
- subjective deletions

Frequently these areas that cannot be harvested are not deleted from the database. They have attributes that contribute to non-timber values, so we leave them in the database but do not allow them to be harvested.

Projecting stand yield

Two sets of yield curves are used in a typical timber supply analysis: one representing development of natural, untreated stands, and another representing managed stands.

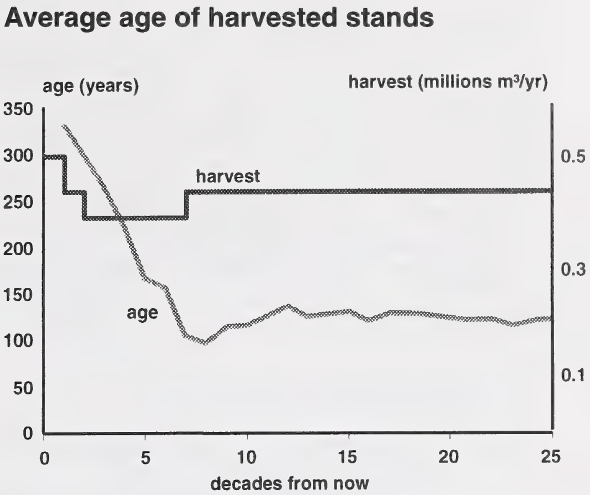

Figure 10. Average harvest age indicator

Our interest at this conference is in stand density management treatments. If such treatments are to have an effect on timber supply, the effects of such treatments must be recognized in the yield tables. To put things simply, if we don't incorporate the effects of stand treatments in the model, they won't show up in timber supply forecasts.

Yield classes

For modeling purposes we usually aggregate stands that have the same attributes and will be managed in the same way. A *yield class* (or *analysis unit* as it is called in British Columbia) is an aggregate of all stands with the same tree species, the same level of site productivity, on which we expect to apply the same management regime, and from which we expect the same growth and yield.

Information used to generate stand yield predictions

The growth and yield information, which is essentially a yield table, is produced with a stand yield projection model (Figure 11). These yield tables represent the way in which stands are expected to develop. So we frequently use different tables for existing or natural stands than for managed or regenerated stands.

Links to forest-level values

When trying to understand how a particular management activity might affect timber supply, it is helpful to identify the mechanism by which timber supply could be affected. Anything we do in the forest affects timber supply through one or more of three types of mechanism:

Predicting stand yield

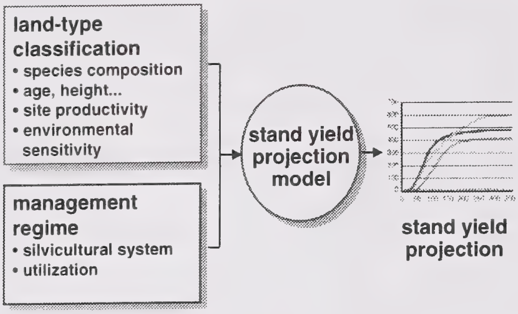

Figure 11. A yield projection model is used to produce the yield tables for timber supply modeling.

landbase effects, growth and yield effects, and policy effects. Understanding the link between silvicultural activities and timber supply requires understanding these effects. While there is overlap among them, it is still helpful to use these categories to guide development of silvicultural regimes and options.

Landbase effects

By *landbase effect*, I mean that a treatment will change the area available for harvesting.

Stand density management can allow some harvesting where it would not otherwise be allowed, e.g. commercial thinning if the stand is younger than minimum harvest age. Treatments can also change the order in which stands become available for harvesting by reducing minimum harvest age. However, on the whole, stand density management activities don't have a significant landbase effect.

Growth and yield effects

As stand managers, we often argue about the final volume yields attributable to a particular stand type under different management regimes. But when we are concerned with timber supply, the timing of availability of the volume yield is often far more important than the final yield itself. For example, when stands reach minimum harvestable size is crucial in many timber supply situations.

In Figure 12, the double headed arrows signify that stand density treatments can be used to alter some important milestones in a stand's development: green-up age, minimum harvestable age, the age at which MAI culminates, and the age above which stands are considered to have old-growth characteristics.

Stand-forest links—growth and yield effects

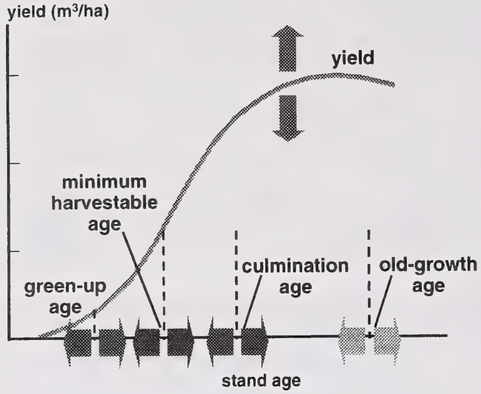

Figure 12. Stand development milestones that can affect timber supply.

By managing stand density, we can influence timber supply, particularly if we focus on the physical attributes of stands rather than their age. For instance, can silvicultural treatments be used to create the physical attributes of old-growth in a stand at a younger age than would otherwise occur? If so, then we can have a significant effect on timber supply in forests where it is constrained by the amount of old-growth.

Proper espacement and precommercial thinning can be used to increase yield. Commercial thinning can be used to produce intermediate yields in stands that would otherwise be excluded from harvesting until they reach minimum harvestable age (Figure 13).

Policy effects—redistributing the harvest

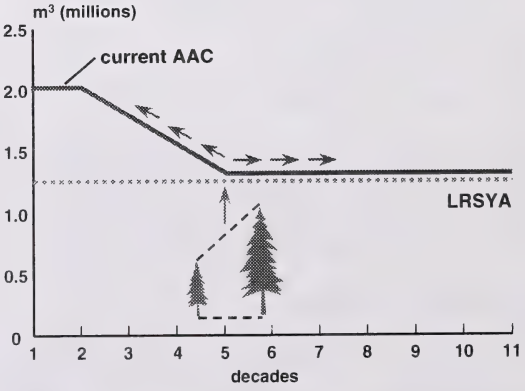

Figure 13. Yields can be affected by certain stand density management treatments.

Policy effects

Policies concerning non-timber values underlie many forest cover constraints in timber supply models. In some timber supply situations these constraints limit timber supply. Green-up and old-growth constraints are the most common examples.

We can affect timber supply in such situations if stand density management treatments can be used to alter the attributes of stands so that the important non-timber values are created sooner or in different amounts than would otherwise be the case.

Policy effects—redistributing the harvest

Timber supply can be very dynamic, and difficult to predict—hence the need for computer modeling. It is not enough to just calculate LRSYA. For example, increasing harvest yield can have an unpredictable effect on the harvest flow (Figure 14). Increasing volume production in decade 5 allows the harvest of some stands to be rescheduled to ages at which yields will be higher. That is, it may release older stands (that were being held because of flow policy constraints) for earlier harvesting, converting them to higher-yield managed stands sooner. It could also allow young stands to be held longer, increasing their production or filling subsequent "holes" in the supply forecast.

Stand-forest links—growth and yield effects

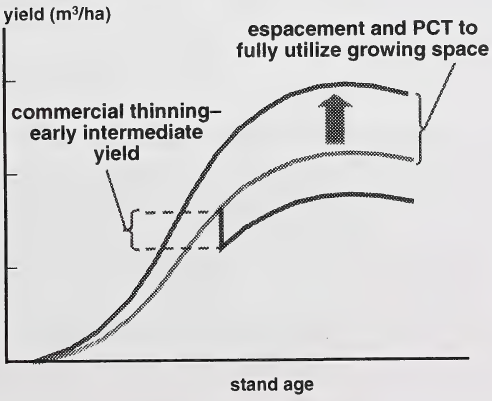

Figure 14. Treatment can redistribute the harvest through time.

Policy effects—increasing the rate of harvest

Silviculture treatments can change the shape of the harvest forecast (Figure 15). Here we see that not only is the LRSYA increased by treatment, but the shape of the forecast is changed as well. The initial harvest level is sustained much longer, the transition is more gradual, and the LTHL is reached later.

Policy effects—increasing the rate of harvest

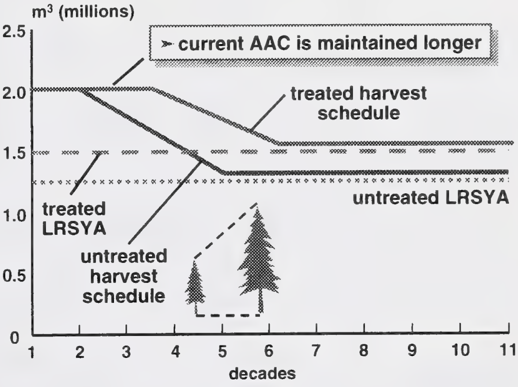

Figure 15. Changing the shape of the harvest forecast.

Analysis-based strategy development

Stands are managed within the context of a larger forest or landscape unit. Therefore, silviculture strategies cannot be based only on stand attributes—a forest-level, analytical approach should be taken. Such an approach involves first defining biologically feasible regime options. Those stands having attributes that make them candidates for treatment will be considered.

Forest-level objectives related to timber supply, targets for specific products (e.g. sawlogs of a specific grade), or employment will be defined in the "landscape assessment" phase of the planning process described in the Alberta Land and Forest Service Interim Planning Manual.

A *regime table* can be used to catalogue feasible treatments, candidate or opportunity areas, and how each contributes to forest-level objectives. Using the results of forest-level modeling (e.g. shadow prices from linear programming), these opportunities can be ranked (Figure 16).

Develop a regime table

Treat-ments	Opportunity Area	Contribution to Objectives	Rank

Figure 16. A regime table can be used to catalogue feasible treatments and candidate areas.

Summary

1. Timber supply is driven by economic forces, shaped by social and environmental values, and limited by the productive capacity of the forest.

2. Stand density treatments influence timber supply through landbase, growth and yield, and policy effects. Understanding the link between silvicultural activities and timber supply requires understanding these effects. Then an objective analytical approach can be used to guide development of regimes, and plan strategic silvicultural programs.

3. If stand density management treatments are to have a recognized effect on forest-level values, they must be worked into a forest-level analysis. If the effect of treatment is not incorporated into the timber supply analysis, no forest-level effect will be recognized.

4. Silvicultural activities cannot be planned based on stand-level objectives alone. A properly constructed forest-level analysis integrates multiple objectives and provides the basis for strategic and tactical planning.

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Stand Density Management in the Context of Forest Management Planning:

Regulations and Linkage to Annual Allowable Cut (AAC) Determination

Daryl Price[1]

This paper will provide an historic policy and legislative overview describing current planning process, specifically the Interim Planning Manual and current timber supply analysis requirements. It will identify Enhanced Forest Management (EFM) or stand density management related issues in AAC determination and then summarize future needs in this area.

It is important to define Enhanced Forest Management. In terms of timber supply analysis, it refers to those specific activities that would increase productivity of stands above levels of unmanaged or basic forest management standards. Specifically it would involve those silviculture activities that would increase growth of individual stands such as juvenile or commercial spacing/thinning (stand density management), genetic improvement, exotic species introduction, and fertilization. It also involves wood quality improvement through stand density management in conjunction with pruning, as well as genetic improvement.

Overview

Alberta operates under the Forests Act, which requires that Forest Management Plans be developed for individual Forest Management Units (FMUs) or Forest Management Agreement Areas (FMAs) under the context of a sustained yield policy. In the past, Alberta's timber supply analysis focussed on developing an AAC within the context of sustained yield management. Most of the other resource users and values were dealt with as constraints on timber supply.

In the early 1970s and on through the early 1980s we introduced a public involvement process into our management planning. Subsequently some of our AAC's developed at that time did take into account some of the public's expectations. For the most part, AACs were based strictly on sustained yield and at that time we developed long-term timber supply guidelines. Although the context of public involvement was limited to integrated resource plans along the Eastern Slopes, we started defining an outline or a set of requirements for management plans being developed at either the FMA or FMU level.

The Alberta Forest Conservation Strategy (AFCS) and government's response, in terms of the Alberta Forest Legacy, signals a change from sustained yield to Sustainable Forest Management (SFM). Forest Management Plans in today's context need to be based on ecological management principles recognizing the limitations of some of our current FMU and FMA boundaries. Over the long term, we will need to move towards larger, more ecologically relevant landscape units for establishing and setting some of our forest management objectives. We now have to operate under an open and consultative approach with intensive and ongoing public involvement. In terms of our planning we are looking at a multidisciplinary planning team with industry, the government and the public as participants. We also have to start to incorporate some of the EFM activities as part of our overall forest management activities.

An Interim Planning Manual was recently put together, which gives us a framework for developing Forest Management Plans. The purpose of having the manual is to update some of our forest management policies. The Planning Manual, signed off in April, 1998, was developed jointly by industry and government participants and provides interim guidance for future changes to forest management. Revisions to the Forests Act and Timber Management Regulation may be required in the future. In addition, policies to address implementation of the Alberta Forest Legacy need to be developed. We also have to deal with Integrated Resource Management (IRM) implementation and a mechanism to facilitate EFM implementation. A current Quota and FMA Tenure Review is underway. Further, we must recognize how we are going to incorporate national and international forest management initiatives.

Next I would like to compare some of the old processes that operated in terms of AAC determination with some of our new approaches. In the past, we were focussing strictly on sustained yield. We had Detailed Forest Management Plan (DFMP) objective guidelines and an outline for how management plans would be prepared. We had a fairly prescriptive set of timber supply guidelines. We looked at developing management plans for individual species and tenure. Most of the other resources were managed as constraints against timber supply.

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[1] Alberta Environmental Protection

As we move into a more adaptive process, we must look at Sustainable Forest Management. The Interim Planning Manual gives some guidelines to develop forest management plans. We also have detailed guidelines in terms of the technical components of AAC determination—what types of information has to be provided and in what context. We would like to set a goal of having one plan developed per unit instead of having individual plans for each species being managed (conifer versus deciduous land base). We also need to take a look at having some sort of landscape assessment. From the landscape assessment we will see allowable cut being one of the outputs.

In addition we have to start to take a look at Integrated Resource Management (IRM) at a much broader level than just the sustained yield unit and having some of our counterparts (e.g. energy sector) as participants on the management development team.

What are some of the components that we would like to see in a Management Plan? At the start of the process we have the development of the Terms of Reference. A Public Involvement Plan identifying the planning team, the local involvement, and how the general public concerns will be brought to the table also needs to be developed.

In terms of the actual Forest Management Plan, we now need to see a definition of resource management philosophy and goals, forest management objectives and strategies and all the various resource supply analysis components.

Unlike the past, we would like to see a mechanism that allows us to view how the actual plan is going to be implemented. There is not much point in doing all the various technical analysis unless there is a way to see how all those details translate into on the ground operations. That will be dealt with in the plan implementation and performance monitoring and stewardship reporting against the assumptions in the management plan.

Timber Supply Analysis Requirements

In terms of achieving the objective of Sustainable Forest Management one of the key aspects is going to be timber supply determination. Timber supply determination is the process followed to obtain the long-term sustainable harvest level for a given area. Two components of resource analysis that we want to see in the management plan are ecosystem/landscape analysis, which is looking at defining the desired future forest state and the objectives (strategies) that will be required to achieve that. Therefore the timber supply analysis is going to be an output of implementing those preferred management strategies. It will be important to define a clear set of management objectives before we begin the analysis phase.

Landscape assessment is the basis for defining a desired future forest state. It forms the foundation for developing resource management objectives. Forest management strategies are tested against objectives, evaluated and then an optimal or preferred option is selected.

What are some of the goals of timber supply determination? We need to obtain a sustainable harvest level taking into account all other uses and resources that are quantifiable. Going though a process of intricate analysis, we will set an AAC for a given area that will meet the strategic planning objectives.

The basic components of timber supply are management objectives, inventory, land base definition and growth and yield. By integrating those four components we can forecast a sustainable harvest level.

An accurate inventory is a critical component of timber supply analysis. Through this inventory we identify the quantity of timber, the quality of timber and the location of timber.

In terms of our management planning process, we have developed a set of guidelines for identifying the types of data and information that are to be provided and document timber supply determination for a given area. In our supplemental guidelines we identify the required data files and documentation that must come as part of the management plan submission. The documentation is broken down into six broad categories—Growth and Yield, Land Base Determination, Timber Supply Analysis Procedures, Summary of Results, Selection and Discussion of Preferred Forest Management Strategy, and Enhancements to Analysis.

1. Growth and Yield

In terms of growth and yield information we need to see a description of the data collection methodology. The actual data sets are to be submitted in digital format (ASCII, dBase IV or SAS Data Format). We would like to see a hard copy of actual code segments listing the coefficients and functions for plot data compilation provided. In terms of the EFM angle—we will a need specific monitoring system (TSPs and/or PSPs) to track silviculture interventions by site and species that we are going to apply in developing that particular AAC.

We would like to see a description of the modeling procedures tested and evaluated during yield curve development. The final proposed yield curves are to be submitted in both hard copy format and digital form. A set of graphs illustrating the associated plot volumes against the yield curves are to be provided. That gives us one mechanism in terms of the validation process. We would like to see a rationale for selecting the proposed yield curves and any adjustments applied in AAC determination. In terms of forecasting yield there will be cases where we will have to cap the maximum volume, or identify a maximum age for harvest in timber supply analysis. Additional documentation requirements are spelled out in the interim planning manual.

2. Land Base Determination

One of the things that is becoming more important as we develop new management plans and shift from the old sustained yield approach to that of sustainable forest management is that we understand the history of any previous analysis. We need to have documentation of the previous inventory that was applied. In terms of the new land base we would like to see a stratification of the land base by land use category. This allows for further modeling opportunities on other resource values. One may not want to exclude areas that could contribute to some other resource value such as old growth timber. We want to see documentation of the process, criteria and assumptions used in obtaining the "net" land base. The actual land base file used in the timber supply analysis must be submitted in complete and digital format (e.g. dBase IV, ASCI, etc.). We need to see an identification of the query protocols used to extract and aggregate the stand level data into the actual input file(s) used in the AAC determination.

3. Timber Supply Analysis Procedures

A technical description of the assumptions, constraints and parameters used in the timber supply analysis is to be provided with both a copy of the input and output data files used in the timber supply model. Constraints are the operational requirements and limitations that may affect the availability and flow of resources. These will need to be assessed to ensure realistic projections of forest growth and associated harvest.

If a spatial timber supply analysis was carried out, both spatial and attribute data representing the final selected management strategy must be provided for review purposes. In terms of forecasting AAC when we start to look at implementing EFM it is important to show intervention strata spatially and temporally over time. Successes and failures must be balanced by silviculture tactic, site and species over the landscape to ensure sustainability.

In terms of EFM, the assumptions, constraints, and parameters must be clearly stated so that performance can be tracked with the rest of the DFMP plan performance. Some of the constraints that should be documented and explained, in the context of the forest management plan objectives include adjacency and green-up requirements, harvest compartment and cut sequencing requirements, access and development limitations, block size limitations, merchantability/economic limitations, reforestation requirements, and those specific constraints associated with other landscape management issues.

4. Summary of Results

At the present time, we have identified four minimum level analyses that should be provided according to our current policies. We need to see analyses that provide a one pass evenflow over two rotations; a two pass evenflow over two rotations; a two pass evenflow for first rotation, step up/down to LRSYA; and finally a detailed calculation of LRSYA by FMU and yield strata. The purpose behind having these various flow patterns over time is to give us some indication as to the limiting factors in AAC determination.

As we shift out of the mode of defining AAC's based on sustained yield to sustainable forest management, it may not be necessary in the future to look at the LRSYA. In terms of our modeling today, we are not looking at regulating the forest and dividing it into equal areas by age class.

We need to see some information summarized from previous management plans to identify how we've shifted from the previous management strategy to the new management strategy. Some information that we need in a general context would be the initial and final age class distributions; growing stock summaries over time; and a forecasting of both the primary and secondary species harvest levels over time.

In order to identify potential allowable cut effects, we would need to look at forecasting a baseline allowable cut and then a new set of AACs based on a specific EFM strategy. Another item that we are interested in looking at is sensitivity analysis. For example, what happens to the future forest condition, and over what timeframe, if projected EFM gains are not realized or the anticipated silvicultural treatments not applied?

5. Selection and Discussion of Preferred Forest Management Strategy

We need to see documentation that leads to the selection of the preferred forest management strategy. Documentation of the rationale for each step of the analysis is required and includes:

1. Species included in AAC determination
2. Harvest system(s) and EFM interventions applied
3. Regenerated yield assumptions
4. Allowances or analysis for natural disturbances
5. The chronology and rationale for alternate runs
6. Long term rate of flow of timber and non-timber resources
7. Evaluation of how the recommended harvest level achieves the preferred forest management strategy and associated objectives proposed in the management plan (e.g. water yield, wildlife habitat, etc.)

One very important factor in Timber Supply Analysis is defining a harvest sequence. The harvest sequence is an output of the preferred forest management strategy and it should be followed, and deviations addressed, at the operational level as well as closing the loop by looking at how the actual AAC is impacted. The sustainability of the timber and non-timber resource values projected in the model is dependent on the harvest sequence being followed. The final harvest sequence requires supporting documentation. In terms of an EFM strategy we need to see how Pre-Commercial Thinnings (PCTs), Commercial Thinnings (CTs) and other EFM interventions take place both spatially and temporally.

6. Future Enhancements to Analysis

It may be necessary to provide analysis enhancements interim to the next scheduled management plan revision. In these cases, it is important to identify areas of the analysis requiring further attention. Additional information in terms of volume sampling may be needed to fill in gaps in data for a particular yield stratum. These enhancements to data need to be documented in the management plan. Most of the EFM related issues would fall in this category.

How does stand density management link to allowable cut determination? There is a direct linkage to forest level age class structures, planting densities, PCTs, and CTs designed to achieve the desired future forest over time and space. AAC credits for EFM effort at the stand level must be assessed in terms of the whole forest age class and wood supply situation. Silviculture is not a series of stand treatments or interventions done on individual stands but a series of treatments planned in time and space in all stands in the forest, designed to achieve the desired future forest (wood flows as well as non-timber objectives).

AACs at the forest level are most sensitive to the amount of operable timber, risk of loss, yield curve shapes, rate of natural stand loss, access, logging costs, current age class distribution, adjacency constraints, green up rules, and site index for both natural and regenerated stands.

Enhanced Forest Management Future Direction and Issues

A critical component of resource management and Enhanced Forest Management is data! Logic tells us, the more we know of the resource that we are trying to manage the more likely we are to meet our management objectives. EFM data and related research in Alberta has been sporadic. We are dependent on models and the other stand density management tools we are learning about at this workshop—however they are not an actual replacement for long-term growth and yield data. Literature review suggests potential EFM gains. These gains must be validated with site specific growth and yield data and further research.

Some of the incentives for EFM and associated policy still need to be defined clearly in the Alberta context. Tenure stability is key to ensure that EFM investment occurs. There needs to be agreement between all tenure holders in the forest area on wood flow and landscape objectives. There is also a need for an EFM agreement between all tenure holders operating in a specific management unit. The need for definition of a baseline is required in terms of AAC determination if dues relief or AAC credit is anticipated.

Is EFM a stand level or forest level benefit? In terms of implementing EFM, we need to take a look at objective-based regeneration standards falling out of the management process itself rather than being an input to the management plan. Regulation driven standards will thwart the benefits of EFM. We need to identify stand parameters for variable regeneration and silviculture standards. We need to develop explicit linkages between stratum yield tables used in AAC determination, to stratum-based regeneration standards and silvicultural treatment. What should be measured at the initial survey, monitored, and linked to forecast yield in the stratum level yield tables will need to be determined.

Until we have long-term Alberta specific actual growth and yield data growth models, stand density management diagrams and crop plans will need to be applied on an interim basis. These will need to be adjusted for Alberta conditions. We require an overall monitoring system for EFM tied into plan performance monitoring at the tree, stand, forest and landscape level. Development of new policies and directives will be required and modified accordingly (adaptive management) as new information is obtained.

Reflecting Density Management Treatments In A Timber Supply Analysis

David J. Presslee[1] and Hugh Lougheed[2]

Weldwood of Canada Limited, Hinton Division manages, under a Forest Management Agreement (FMA) with the Province of Alberta, about 1 million hectares of Crown forest near Hinton, Alberta. Under this agreement, the company can propose management strategies to enhance the allowable annual cut within a sustained yield framework to meet future mill requirements.

Currently, the company is investigating ways to enhance the annual allowable cut (AAC) of the FMA area. This is intended to optimize short-term fiber supply options and to guard against possible purchase fiber shortages or other AAC losses arising from land base pressures and stewardship commitments. Because the Company is already harvesting the full AAC from the FMA area, there is little opportunity to increase or even maintain current fibre production without intensifying the management of these lands (Weldwood 1996). Density management alone or in combination with other silvicultural treatments is one strategy the company is evaluating to enhance the AAC.

Density Management: A Strategy to Enhance AAC

Density management is the orderly discipline of establishing and maintaining forest crops at a density that is consistent with the management objective (modified from Smith 1986). By applying *proper* density management, stands can be established or thinned to a level that ensures full utilization of the growing space. Thinning can enhance yields where it is designed to accelerate merchantable yield or to capture mortality from stands experiencing loss.

The emphasis on *proper* density management is intentional. The formulation of a density management regime is a demanding and critical process involving the evaluation of stand-level (biological) responses, forest structure (age class distribution), and physical and economic viability. To achieve our AAC objective, we are developing density management regimes using five basic steps:

1. conducting an initial forest-level analysis to identify opportunities to increase AAC,
2. identifying alternative stand-level regimes that match forest-level opportunities,
3. developing ecologically based yield curves for the most promising treatment regimes,
4. selecting those regimes which produce the desired AAC objective at an acceptable quality and cost, and
5. developing a detailed implementation and monitoring plan.

Initial Forest Level Analysis

An initial forest analysis was conducted to assess the potential of different density management strategies to increase both the short-term and long-term AAC. This analysis indicated that the limiting factor to increasing the current AAC is the amount of growing stock available for harvest during the "transition period" from harvesting natural stands to harvesting second growth (Figure 1). Management strategies that increase available growing stock by either accelerating the development of young stands, or by capturing the mortality in stands experiencing loss during this transition period, will result in an AAC benefit.

Accelerating the Development of Young Stands

Juvenile spacing, by accelerating the development of merchantable yields in young stands, increases the rate at which existing mature stands can be harvested. Based on a literature review and re-measurement of Company and Canadian Forest Service pre-commercial thinning trials (Presslee and Navratil 1997), we have concluded that pre-commercial thinning will:

- Significantly increase the short-term merchantability, sawlog yields and value production in regenerated stands following harvest;
- Increase total and merchantable volume production in very dense fire origin stands under specific site conditions; and
- Set up both types of stands for a profitable first thinning (CT1) and a high value two-thinning (CT1+CT2) regime.

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We estimate that pre-commercial thinning can improve merchantable yields at 80 years by up to 30 percent in dense logging origin stands (Presslee and Navratill 1997) and up to 100 percent on excessively dense fire origin stands (Udell and Dempster 1987).

Conserving Growing Stock by Capturing Mortality

In contrast to pre-commercial thinning, the estimates of merchantable and total volume production increases achievable by commercial thinning is less well documented and suffers from the lack of long-term local data (Navratil 1997). Despite this, we have been able to develop some preliminary interpretations based on available literature, European data and expert opinion and we conclude that commercial thinning will:

- Increase total yield, where it captures mortality,
- Increase merchantable sawlog production, and
- If properly executed, increase both volume and merchantable production.

One estimate shows on high productivity lodgepole pine sites, mid- to late-rotation commercial thinning regimes can generate an incremental merchantable volume of 50 to 100 m^3/ha in one-thinning regimes and potentially 100 to 180 m^3/ha in two-thinning regimes (Smithers 1957).

Developing Yield Curves

It is relatively straightforward to demonstrate the potential of density management treatments based on individual trials and studies. The real challenge, however, is to develop "reasonable" yield functions that cover a range of treatments over a range of stand types and ecosystems.

In developing yield curves, we have developed an ecological and ecosystem-specific approach. This is necessary because each tree species is adapted to a certain range of environmental conditions, and, as such, its growth and behavior in response to treatment will depend upon the ecosystem in which it grows (Klinka and Carter 1984). Research on our FMA area has demonstrated that the processes of stand differentiation, crown and stand development and mortality are all affected by site characteristics in addition to the obvious density dependent relationships (Ives and Rentz 1993, Presslee and Navratil 1997, Geographic Dynamics Corp 1998).

Fundamental to the implementation of an ecological approach is the "working group." A working group is a collection of ecologically similar sites that are managed to a particular silviculture regime and objective (modified from Courtin *et al* 1989) and therefore, expected to respond similarly to treatment (Figure 2). This provides a unique bridge between planning at the forest level and actions taken at the stand level. The working group is the platform from which to achieve higher yield gains from site-specific treatments by better forecasting treatment opportunities and response.

To improve our yield estimates of density management treatments, each working group was further stratified. The hierarchical classification in descending order for each working group is as follows: yield group, natural subregion, crown closure, tree productivity rating class, and age class. While this initial subdivision provided an extremely large matrix, it is expected that we can eventually reduce the number of cells without compromising the effectiveness of the projections.

Using this stratification as a basis, five steps were used to develop enhanced management yield curves:

1. Permanent growth sample and regenerated stand yield inventory data were analysed to determine stand structure parameters for each strata (Forestry Corp. 1998, Golder and Associates 1998).
2. Using the stand structure information, several stand density management regimes were designed for each strata using stand density index, spacing factor, thresholds of basal area removal and other information synthesised from literature review.
3. Customised Tree and Stand Simulator (TASS) (Mitchell 1975) runs were produced for each stand density management regime. By bracketing combinations of treatments (PCT, CT and fertilization), timing and intensity, we were able to determine a preferred regime. Incremental enhanced management yields were calculated as the difference between the treatment regime and a base (no treatment) run.
4. Enhanced management yield curves were then calculated by applying the incremental yields to the appropriate fire- or regenerated stand yields (Figure 3).
5. Selected TASS runs were then compared to results from various trials and output from Forest Projection System (Arney 1995) and Mixedwood Stand Projection System (Reimer 1991) runs as an independent check of TASS results.

Analyzing The Options

Forest-level timber supply analyses are required to assess the benefits of alternative density management regimes. Key questions to be answered include:

- Will density management achieve the desired

AAC effect?

- What area would have to be treated to achieve the AAC gain?
- What is the cost of the incremental AAC?
- Are there synergies with other treatments?
- Are the wood qualities acceptable?

In making this assessment it is essential that we make reasonable assumptions regarding potential stand yields, feasibility of treatments, forest practice restrictions, integrated resource management objectives, and future land withdrawals.

In reviewing the costs of benefits of density management and other enhanced management treatments, we have generally concluded that we can produce substantial incremental volume from the FMA area at a lower delivered cost than purchasing this wood on the open market. However, with increasing investment, the cost of incremental volume realised will rise sharply, reflecting the law of diminishing returns and will at some point rise above the cost of purchased fibre (Figure 4). Regardless of the level of investment the total volume that can be produced on the FMA area is limited by the biological capability of the forest estate.

Finally, it is the role of the timber supply analyst to summarize the alternatives and present that information for management consideration. It is their decision, in light of all of the costs and benefits, to determine which alternative is desirable. In making this decision, managers must be aware that AACs calculated assuming enhanced treatment regimes comprise a clear commitment. The assumed growth and yield performance of the enhanced regimes becomes "the standard," incremental to existing plans or legislation. Similarly, future decisions affecting either the timing or amount of expected yield gains would have to be made in light of the resulting effect on AACs.

Implementation and Monitoring

Using the approved management strategies as a basis, an implementation plan will be developed. An essential component of this plan will be the establishment of annual and cumulative measures for annual performance reporting and review. By monitoring performance targets to detect errors in the assumed stand and forest dynamics, periodic adjustments to treatment types, timing or amounts would be designed to maintain the assumed yield increases—thereby conserving the integrity of the AAC (Figure 5).

Summary

The formulation of a density management regime is a demanding and critical process involving the evaluation of stand-level (biological) responses, forest structure (age class distribution), and physical and economic viability. Where density management treatments are used to determine the annual allowable cut, these treatments will become the new basic silviculture levels replacing the current legislated standards. Once a regime is selected and included in the AAC, it must be maintained to continue the benefits. Finally, adaptive management is paramount to maintaining the integrity of the AAC.

Acknowledgement

Special thanks to Dr. Stan Navratil for his thoughtful review of this paper, and for his singular contribution to the Weldwood enhanced forest management program.

Allowable Cut Effect

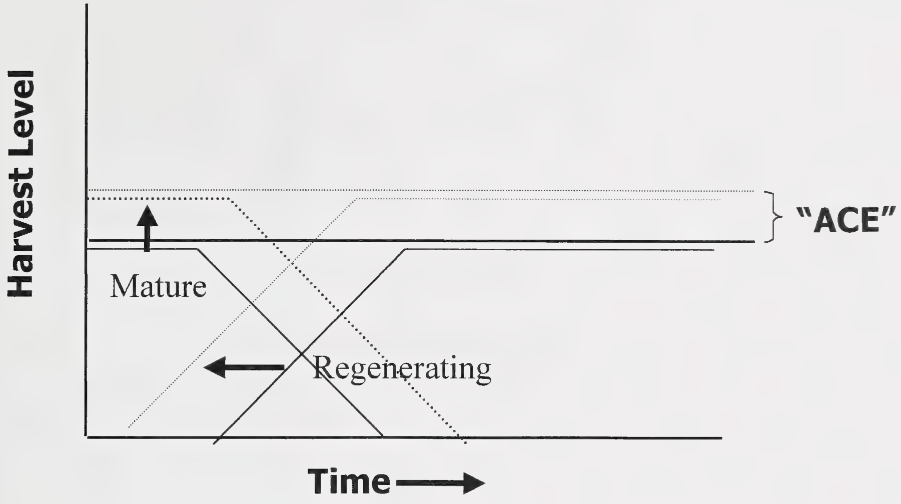

Figure 1. Management strategies that increase growing stock available to harvest during the transition period will result in an allowable annual cut benefit

Working Groups

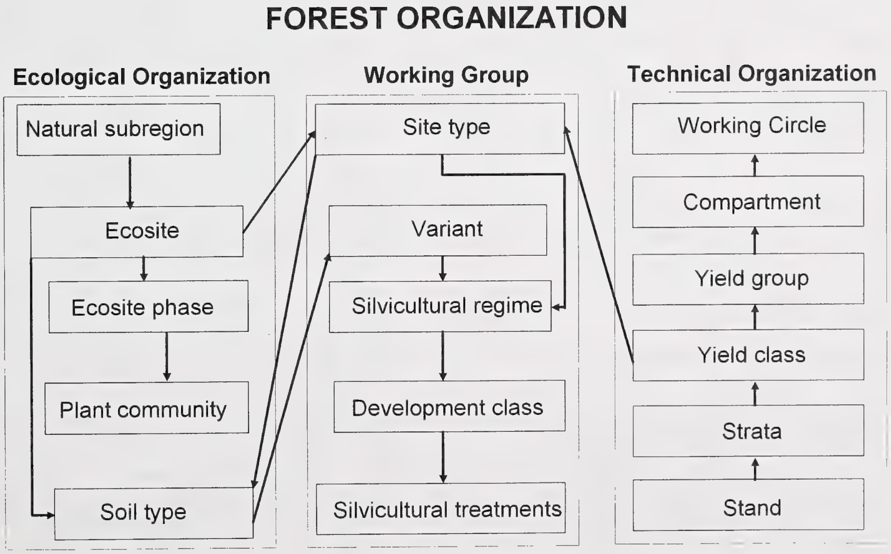

Figure 2. The working group bridges forest-level plans to stand-level actions.

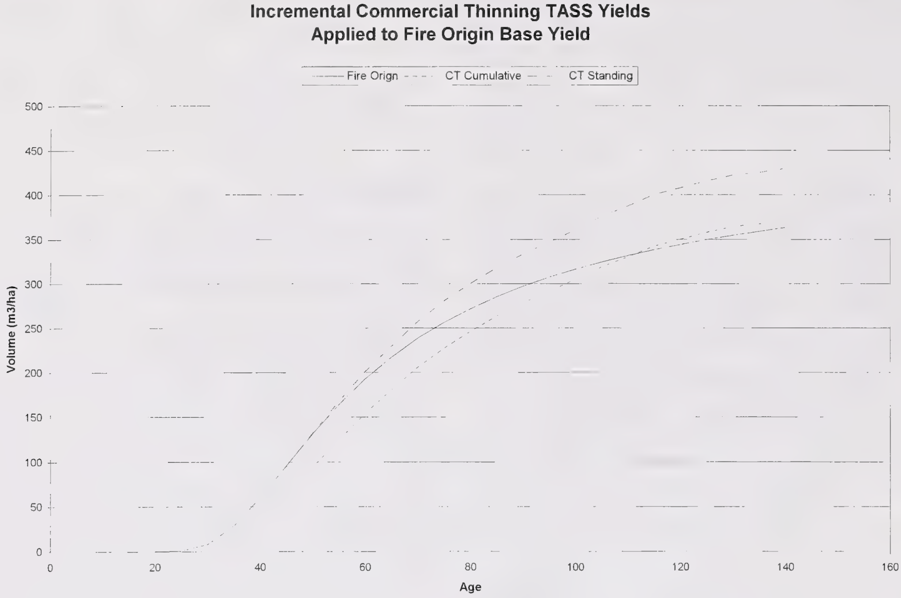

Figure 3. Example enhanced management yield curve. Incremental commercial thinning TASS yields applied to fire origin base yield.

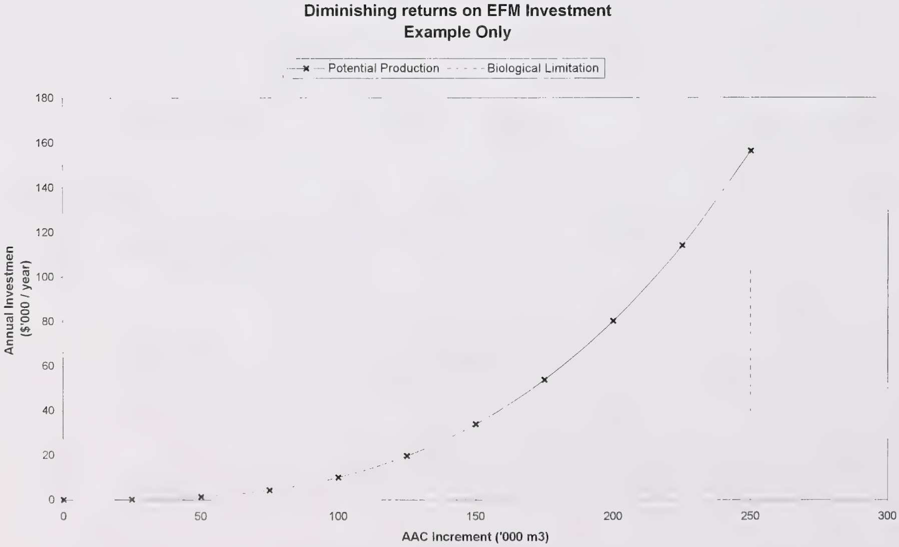

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Figure 4. Theoretical "production possibility" relationship.

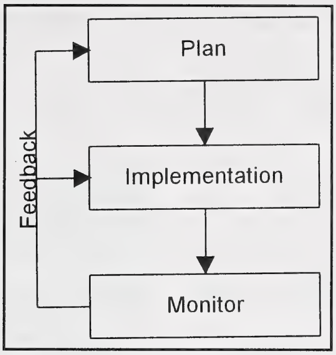

Figure 5. Maintaining the integrity of the AAC through adaptive management.

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Simulating Forest-Level Effects of Stand Density Management

Ted Gooding[1] and Willi Fast[1]

Introduction

Timber resources for industrial use in Alberta are approaching full commitment. The increasing influence of non-industrial stakeholders is affecting forest land use decisions, and raises the potential for erosion of the industrial forest landbase.

Forest companies in Alberta are trying to maintain or increase the level of timber harvest where they have operating rights. In response to increasing landbase pressures from third party interests, forest managers are considering enhanced forestry techniques for improving the quality and quantity of timber products flowing from land they manage.

Enhanced forest management (EFM) techniques currently being assessed and/or undertaken by various Alberta companies include control of competing vegetation, tree improvement, fertilization, juvenile spacing, pre-commercial thinning (PCT) and commercial thinning (CT). The latter three can collectively be referred to as density management techniques.

To date, most of the effort in enhanced forest management has been aimed at improving the success of operational techniques, and at monitoring stand-level responses to various types and levels of treatments. This has largely been a quest for developing more efficient treatment methods, and for developing an understanding of biological responses to treatments. These efforts have been focussed at the stand level, where treatments are applied and responses are measured.

Far less effort has been expended in Alberta on understanding the impacts of stand-level treatments on long term timber flow at the forest level. The interactive effects of age class distribution, species composition, timber yield curve form, forest management policy, and level of EFM investment on sustainable harvest levels are poorly understood. These effects are rarely considered in stand-level decision making. EFM investments have typically not been evaluated from a long term strategic view at the forest level.

Interest in EFM is occurring in a context of increasing uncertainty. The policy and regulatory framework under which EFM will be implemented in Alberta is incomplete. For EFM to be evaluated in this context at the forest level, significant policy and management planning assumptions must be made. In addition, the biological growth responses to most EFM treatments for stand types in Alberta are largely unknown.

Uncertainties regarding policy and regulatory environment, management planning objectives and assumptions, and treatment responses suggest that sensitivity analyses would be helpful in evaluating EFM alternatives, and in identifying those instances where EFM is justifiable.

Objectives

This paper uses a simulation approach for evaluating the impacts of stand density management treatments on sustainable harvest levels. Three specific objectives are addressed:

1. Determine the forest-level age class structures where stand density management is or is not appropriate.
2. Determine the impacts of different silviculture treatment response assumptions on forest-level estimates of sustainable harvest level.
3. Determine the impacts of different policy and planning assumptions on forest-level estimates of sustainable harvest level.

Methods

WOODSTOCK™ based forest-level simulations were completed for an array of management scenarios. Management scenarios were combinations of Forest Structure, Silviculture Treatment, and Management Strategy. These were combined in a factorial arrangement of:

1. 4 Forest Structures
2. 6 Silviculture Treatments
3. 3 Management Strategies

In all, a total of 72 management scenarios were simulated (i.e. 4 x 6 x 3 = 72).

Forest Structures

Four hypothetical Forest Structures were created. All forests were pure lodgepole pine with age class structures

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classified as:

1. Regulated
2. Young
3. Old
4. Typical

The *Regulated Forest* structure had an equal area in each five year age class from 5 to 125, with a mean age of 60. The regulated forest was the objective of traditional forest management techniques such as area control.

The *Young Forest* structure had an age class distribution skewed toward the younger ages, with an area weighted mean age of 36 years (Figure 1). This structure typifies a forest which has been subject to frequent stand replacing disturbances in old age classes.

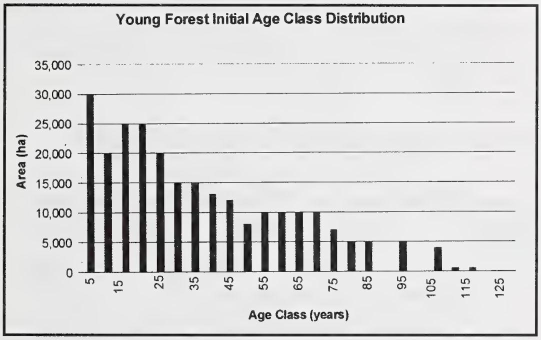

Figure 1. Initial age class distribution of Young Forest.

The *Old Forest* structure had an age class distribution skewed towards the older ages, with an area weighted mean age of 92 years (Figure 2). Such a structure could arise where forests are excluded or protected from disturbance for protracted periods.

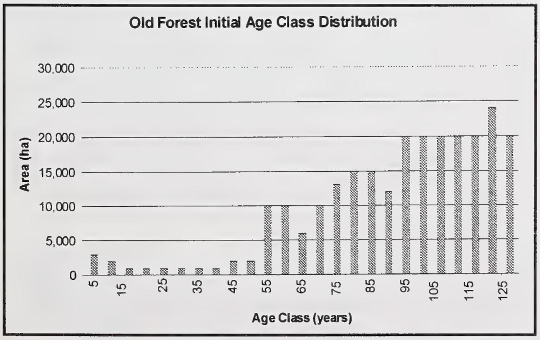

Figure 2. Initial age class distribution of Old Forest.

The *Typical Forest* structure had an age class distribution with numerous pronounced gaps (i.e. missing age classes), and heavily weighted to a small number of age classes (Figure 3). The area weighted mean age was 65. This forest structure is typical of many of Alberta's tracts of fire-origin lodgepole pine.

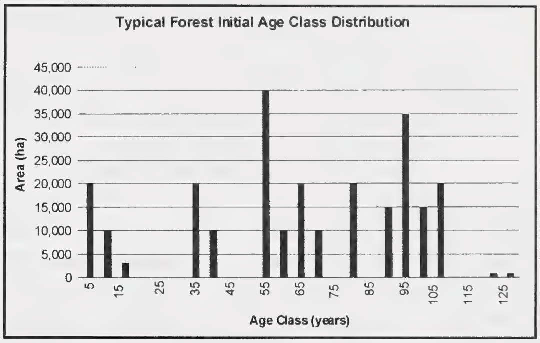

Figure 3. Initial age class distribution of Typical Forest.

Silviculture Treatments

Six commercial thinning treatments were defined. All consisted of a 30% volume removal, and occurred only at 50 years of age. The six thinning treatments consisted of variable volume recoveries relative to the *No Thin* treatment as follows:

1. ***No Thin***
    - no commercial thinning treatment
    - volume accumulates at same rate as natural stand yield curve
    - eligible for final harvest at 70 years of age

2. ***No Recovery***
    - no volume recovery after commercial thinning treatment
    - residual volume tracks at 70% of natural stand yield curve starting at 50 years
    - eligible for final harvest at 70 years of age

3. ***Thin & Same***
    - no cumulative volume recovery after commercial thinning treatment
    - residual volume accumulates at same rate as natural stand yield curve, but starts at 70% of natural stand volume at 50 years.
    - eligible for final harvest at 70 years of age

4. ***20-Year Recovery***
    - residual volume recovers to natural stand yield curve 20 years after treatment, and follows

  - natural stand yield curve thereafter
  - eligible for final harvest at 70 years of age

5. ***30-Year Recovery***
   - residual volume recovers to natural stand yield curve 30 years after treatment, and follows natural stand yield curve thereafter
   - eligible for final harvest at 80 years of age

6. ***40-Year Recovery***
   - residual volume recovers to natural stand yield curve 40 years after treatment, and follows natural stand yield curve thereafter
   - eligible for final harvest at 90 years of age

The yield curve for each of the six treatments is shown in Figure 4. The *No Recovery* and *Thin & Same* treatments represent very conservative (pessimistic) assumptions about thinning treatment responses. In contrast, the *40-*, *30-*, and *20-Year Recovery* treatments represent increasingly aggressive (optimistic) thinning responses.

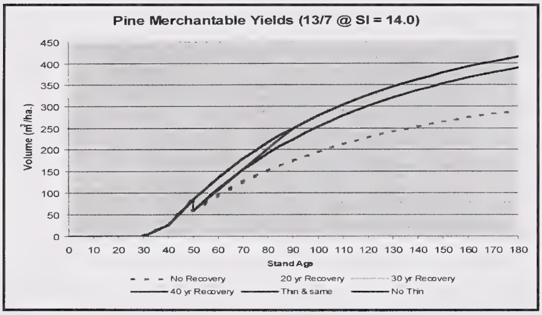

Figure 4. Yield curves for the six silviculture treatments.

Management Strategies

The planning horizon for all management strategies was 180 years. Final harvest was by clearcutting, and all stands were regenerated to the same (natural stand) yield curve with no regeneration delay. The minimum harvest eligibility age for clearcutting of natural stands was 70 years. Thinning treatments were eligible for final harvest at the ages defined above. The objective function maximized harvest volume.

Three Management Strategies were defined. They consisted of different constraints for harvest volume flow and residual forest age structure as follows:

1. ***No Cover Constraints Strategy***
   - even harvest volume flow over planning horizon
   - no constraints for residual forest age structure

2. ***Normal Constraints Strategy***
   - even harvest volume flow over planning horizon
   - minimum 5% of forest area must be greater than 100 years old, and
   - minimum 10% of forest area must be greater than 80 years old

3. ***Variable Harvest Volume Strategy***
   - allow a 2% variation in harvest volume for each consecutive 5-year period through the planning horizon
   - minimum 5% of forest area must be greater than 100 years old, and
   - minimum 10% of forest area must be greater than 80 years old

The *Normal Constraints Strategy* could be considered a "typical" strategy for forest management planning in Alberta. The *Variable Harvest Flow Strategy* is not typically entertained under the current regulatory framework in Alberta.

Results (Tables and figures follow)

Forest Structure and Thinning Treatment AAC Effects

Annual Allowable Cut (AAC) estimates for the *No Cover Constraints* strategies are listed in Table 1 and displayed in Figure 5. Forest Structure effects were significant. The *Young Forest* had significantly lower AAC estimates than all other forest structures. On an absolute basis, commercial thinning treatment effects were marginally variable. When expressed in percentage terms as relative increases over the *No Thinning* treatment, the *20-*, *30-*, and *40-Year Recovery* treatments showed significant effects (Figure 6, below).

AAC estimates for the *Normal Constraints* strategies are listed in Table 2 and displayed in Figure 7. Again, Forest Structure effects were significant, with the *Young Forest* having significantly lower AAC estimates than all other forest structures. On an absolute basis, commercial thinning treatment effects were marginally variable. When expressed in percentage terms as relative increases over the *No Thinning* treatment, the *20-*, *30-*, and *40-Year Recovery* treatments again showed significant effects (Figure 8).

AAC estimates for the *Variable Harvest Volume* strategies are listed in Table 3 and displayed in Figure 9. Again, Forest Structure effects were significant, with the *Young Forest* having significantly lower AAC estimates than all other forest structures. The differences were not as large as for the *No Cover Constraints* and *Normal Constraints* strategies. On an absolute basis, commercial thinning treatment effects were marginally variable. When expressed in percentage terms as relative increases over the *No Thinning* treatment, the *20-, 30-*, and *40-Year Recovery* treatments again showed significant effects (Figure 10).

Forest Management Strategy AAC Effects

The different forest Management Strategies had significant effects on AAC, with the most dramatic effects evident for the *Young Forest* (Figure 11). For all commercial thinning treatments, the *Normal Constraints Strategy* showed significantly lower AACs than the other forest management strategies. This effect was constant across thinning treatments.

Forest Structure and Thinning Treatment Growing Stock Effects

Using growing stock (m^3) as an indicator, Forest Structure had a significant effect, across thinning regimes. Under the *Normal Constraints Strategy* with *No Thinning*, growing stock continually decreased over time for all Forest Structures except the *Young Forest* (Figure 12). For the *Young Forest*, growing stock continued to increase over time. In the *Young Forest*, this was the case even when the most aggressive thinning response was introduced (Figure 13).

The growing stock trends in the *Young Forest* were different under the *Variable Harvest Volume Strategy*. After an initial increase, growing stock in the *Young Forest* followed the same stable (or slightly declining) trend as for the other Forest Structures (Figure 14).

Forest Structure Effects on Percentage of Harvest Volume from Thinning

The percentage of annual harvested volume from thinning was significantly different among Forest Structures. For the *Young Forest* under the *Normal Constraints Strategy*, thinning accounted for a significant percentage of the harvested volume in the first four decades of the planning horizon (Figure 15). This was the case for all thinning treatments. In the *Typical Forest* under *Normal Constraints*, thinning volumes were not as large initially, and accounted for a larger proportion of the total harvest later in the planning horizon (Figure 16).

Discussion

As might be expected, more aggressive growth responses to commercial thinning treatments resulted in higher gains in AAC. This effect was consistent across Forest Structures and Management Strategies. However, the magnitude of gains in AAC due to thinning treatments were relatively small, especially when compared to the effects of Forest Structure and Management Strategy on AAC.

Under each of the three Management Strategies, AACs were significantly lower for the *Young Forest* than all other Forest Structures. Initial growing stock was not sufficient to allow higher levels of sustainable harvest in the *Young Forest*.

This problem was alleviated somewhat by relaxing the constraint of even harvest volume flow. When the annual harvest level was allowed to increase among periods in the *Young Forest*, the AAC differences between the *Young Forest* and the other Forest Structures were significantly smaller (i.e. increased AAC in the *Young Forest*). A similar increase in AAC due to relaxing of the even harvest volume flow constraint was not seen for the other Forest Structures. Other constraints to harvest level were more important than even-flow for those Forest Structures.

The forest cover constraints were significant for all Forest Structures. AACs were lower for all Silviculture Treatments and Forest Structures under *Normal Constraints* versus *No Constraints*. Both of those Management Strategies had even-flow constraints, but the *No Constraints* strategy had no forest cover constraint. The forest cover constraint of the *Normal Constraints* strategy was significant, especially in the *Young Forest*, where the lack of growing stock in older age classes severely limited the annual harvest. None of the Silviculture Treatments were able to ameliorate that effect.

Forest Structure effects on growing stock were significant. Because of the limited growing stock in older age classes in the *Young Forest*, initial annual harvests were restricted. If even-flow constraints were in place, initial harvest levels could not rise in later periods when more growing stock became merchantable. Therefore, growing stock increased over time, because the harvest level could not increase. When the even-flow constraint was relaxed under the *Variable Harvest Volume Strategy*, growing stock in the *Young Forest* more closely followed that of the other Forest Structures.

Under *Normal Constraints* in the *Young Forest*, the initial harvest was limited by the availability of timber in the merchantable age classes. In order to maximize harvest levels, WOODSTOCK™ thinned very heavily in the early periods (i.e. large proportion of harvest volume from thinning). This extracted volume from stands which otherwise would not have been operable. Therefore, AAC in the *Young Forest* was increased significantly by the introduction of thinning, no matter how aggressive the growth response. The AAC effect in this case was not due to a stand-level growth response, but rather to a forest-level effect of being able to access volume early in the planning horizon which would not have been available without commercial thinning.

In the *Typical Forest*, proportions of harvest volume from thinning were much lower early in the planning horizon. Initial harvest was not limited by growing stock, and WOODSTOCK™ did not rely on thinning volume early on. However, later in the planning horizon, when forest cover constraints limited access to older age classes, a higher proportion of harvested volume came from thinning. Again, an increase in AAC was possible through the introduction of thinning, but this was not a direct stand-level effect. Rather, thinning made it possible to access merchantable volume at a time in the planning horizon when those stands would not have been available in the absence of thinning (i.e. thinning was possible in stands as young as 50 years, whereas in the absence of thinning, stands were held to age 70 prior to clearcutting).

Forest-level mean annual increments (MAIs) were less variable among Silviculture Treatments than stand-level MAIs. The Forest Structure and Management Strategy effects discussed above dampened the stand-level MAI differences observed in the yield curves for different Silviculture Treatments. This emphasizes that observed stand-level treatment effects are not directly transferable to the forest level.

Conclusions

As stand-level growth responses to commercial thinning treatments improve, corresponding increases in AAC are possible. Those AAC increases, however, may be small in comparison to the effects of forest-level impacts. Forest-level impacts may even negate the positive AAC influence of stand-level treatment responses. Two forest-level parameters with demonstrated influence on the AAC effects of thinning are age class structure and forest management strategy.

The influence of forest-level parameters emphasizes the importance of basing forest management decisions on more than just stand-level growth response inputs. Depending on forest-level circumstances, commercial thinning may or may not be justifiable, and known growth responses to treatments at the stand-level may or may not be important.

In the absence of long term growth response data for proposed silviculture treatments, forest-level sensitivity analyses are useful exercises to understanding the importance and impacts of stand-level treatment decisions.

Commercial Thinning Treatments	Forest Structures			
	Young	Typical	Regulated	Old
No Thin	596,752	791,674	797,028	873,941
Thin No recovery	623,731	796,225	801,667	879,651
Thin 20 recovery	675,903	850,878	859,581	925,276
Thin 30 recovery	619,079	842,459	851,916	918,189
Thin 40 recovery	609,791	833,924	842,718	911,933
Thin & same	649,030	803,768	809,147	886,325

Table 1. Annual allowable cut (AAC m^3/year)—No Cover Constraints Strategy.

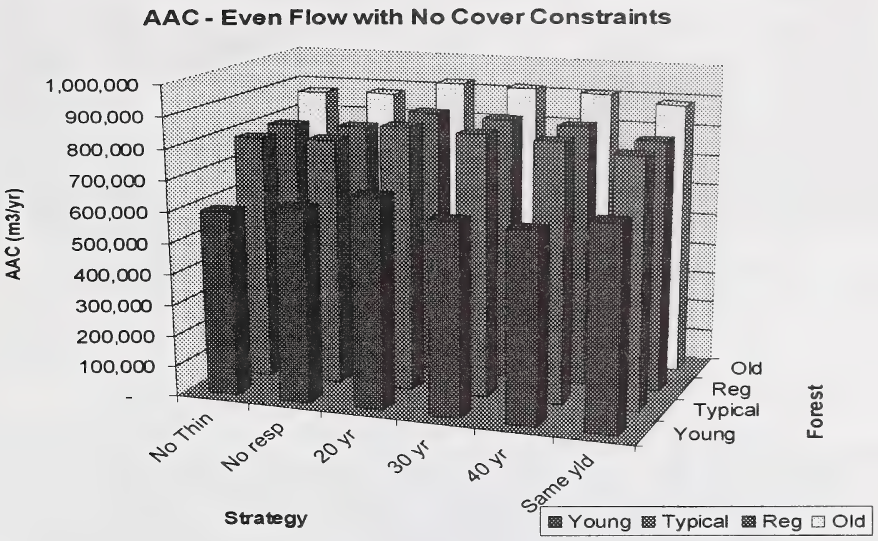

Figure 5. Annual allowable cut (AAC)—No Cover Constraints Strategy.

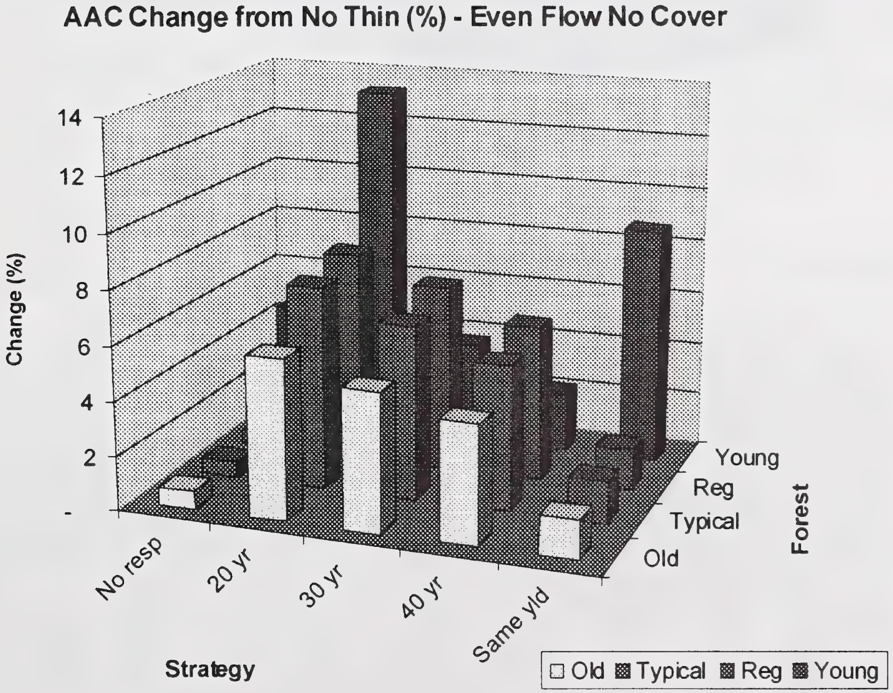

Figure 6. Per cent change in annual allowable cut (AAC) for thinning treatments compared to No Thinning Treatment—No Cover Constraints Strategy.

Commercial Thinning Treatments	Forest Structures			
	Young	Typical	Regulated	Old
No Thin	412,072	767,005	772,634	847,667
Thin No recovery	458,298	773,893	779,929	856,851
Thin 20 recovery	472,324	823,059	832,234	896,599
Thin 30 recovery	447,878	818,934	828,535	892,873
Thin 40 recovery	444,394	810,731	819,994	887,141
Thin & same	467,427	782,243	787,819	863,219

Table 2. Annual allowable cut (AAC m^3/year)—Normal Constraints Strategy.

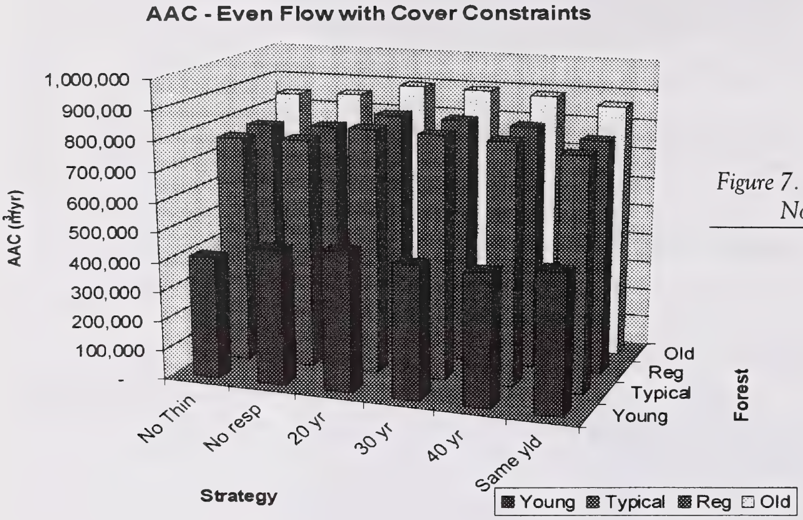

Figure 7. Annual allowable cut (AAC)—Normal Constraints Strategy.

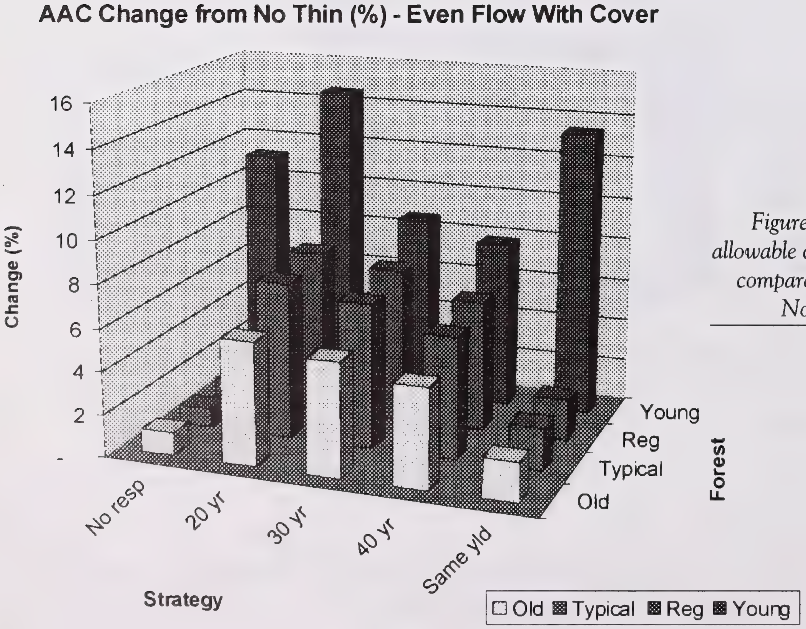

Figure 8. Per cent change in annual allowable cut (AAC) for thinning treatments compared to No Thinning Treatment—Normal Constraints Strategy.

Commercial Thinning Treatments	Forest Structures			
	Young	Typical	Regulated	Old
No Thin	574,633	779,743	785,319	865,341
Thin No recovery	635,971	788,425	793,856	873,926
Thin 20 recovery	659,890	836,274	845,919	918,184
Thin 30 recovery	622,046	833,899	843,792	915,279
Thin 40 recovery	613,428	827,558	838,428	909,203
Thin & same	650,340	793,816	799,803	880,433

Table 3. Annual allowable cut (AAC m^3/year)—Variable Harvest Volume Strategy.

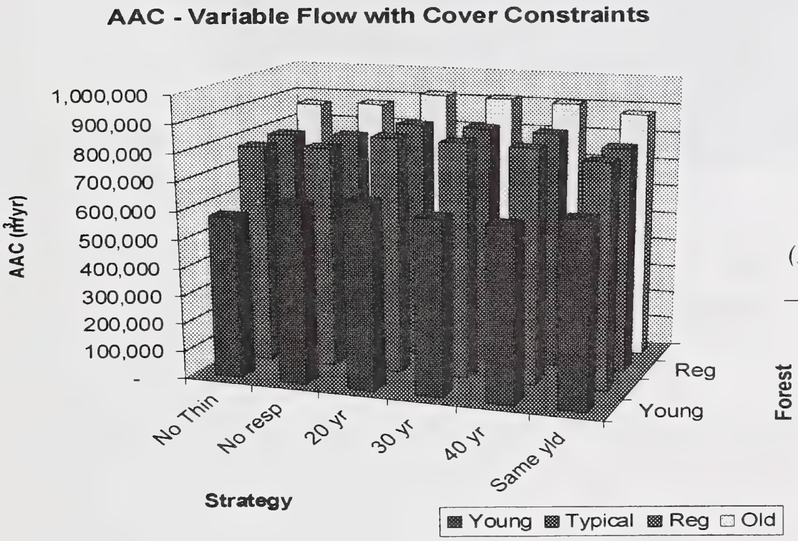

Figure 9. Annual allowable cut (AAC)—Variable Harvest Volume Strategy.

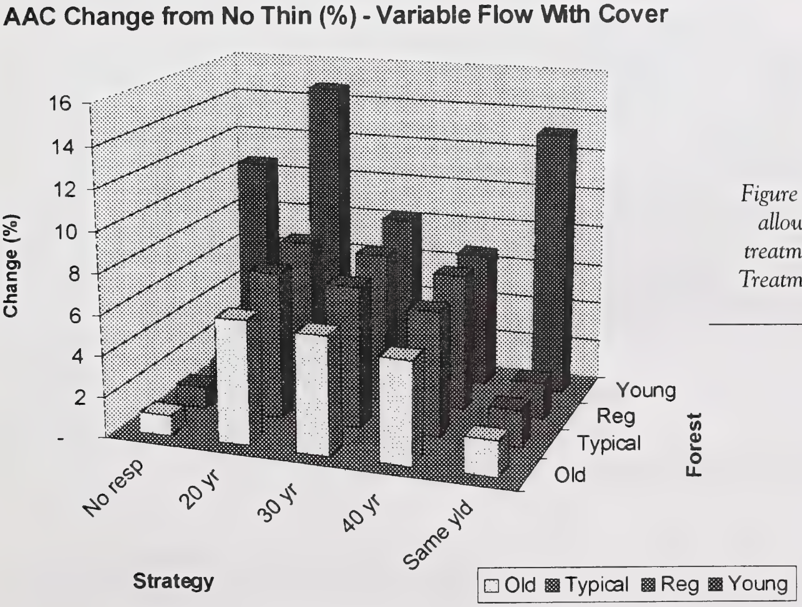

Figure 10. Per cent change in annual allowable cut (AAC) for thinning treatments compared to No Thinning Treatment – Variable Harvest Volume Strategy.

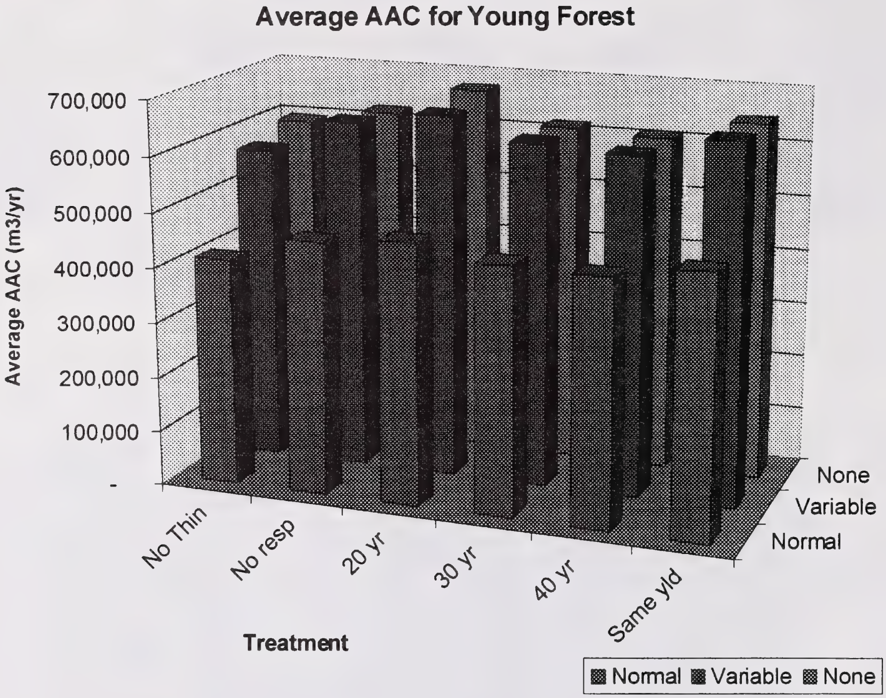

Figure 11. Forest management strategy effects on AAC for the Young Forest.

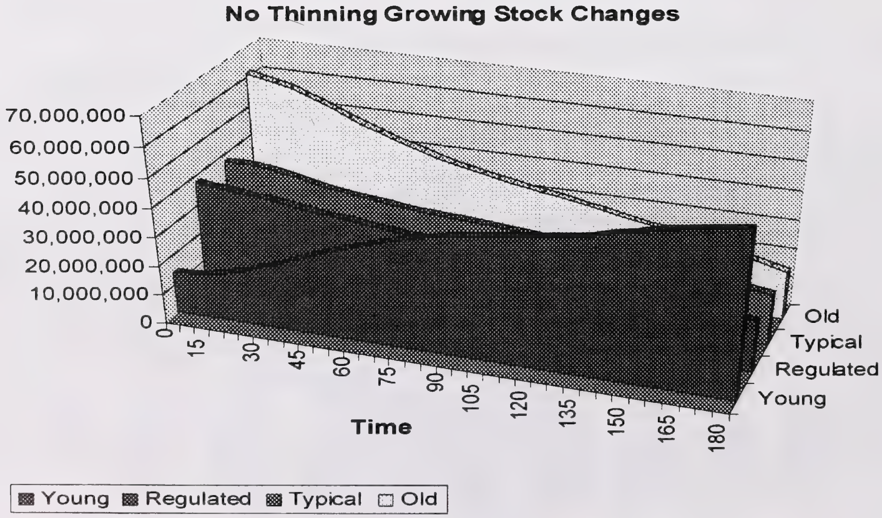

Figure 12. Forest Structure growing stock (m³)effects for No Thinning treatment under Normal Constraints Strategy.

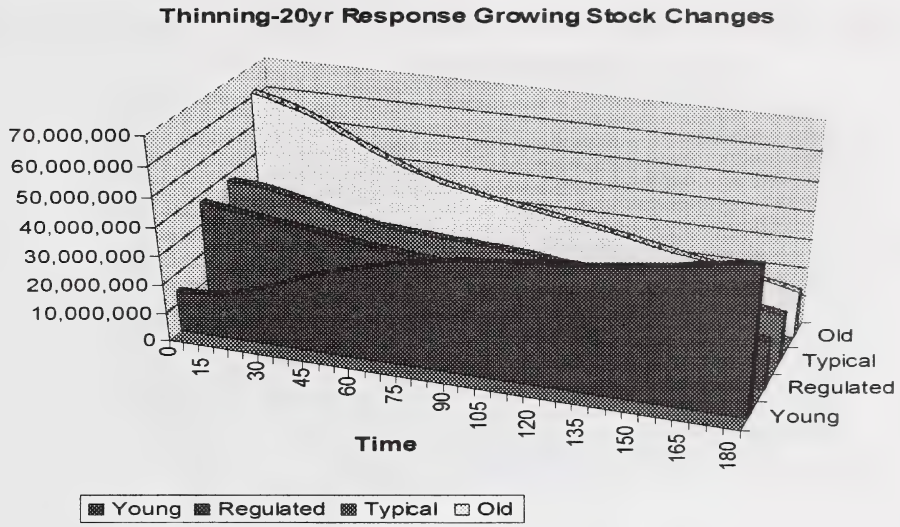

Figure 13. Forest Structure growing stock (m³) effects for 20 Year Thinning Response treatment under Normal Constraints Strategy.

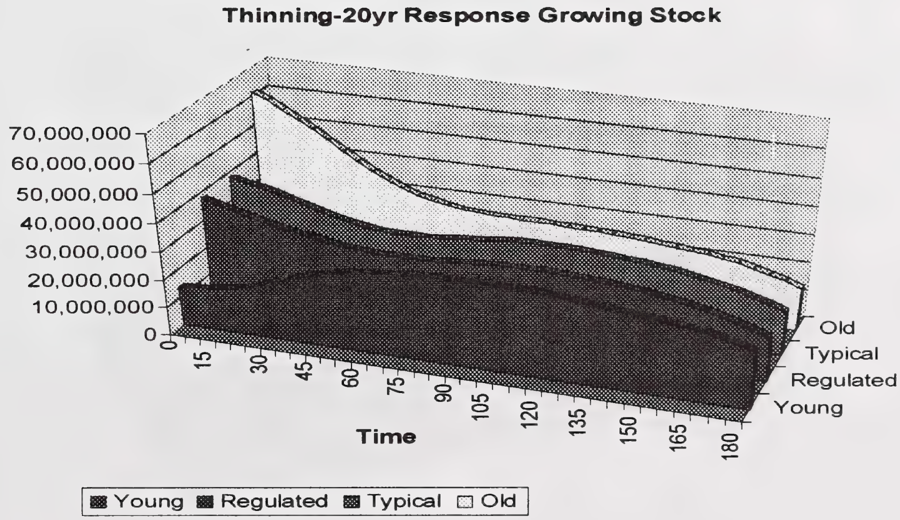

Figure 14. Forest Structure growing stock (m³) effects for 20 Year Thinning Response treatment under Variable Harvest Volume Strategy.

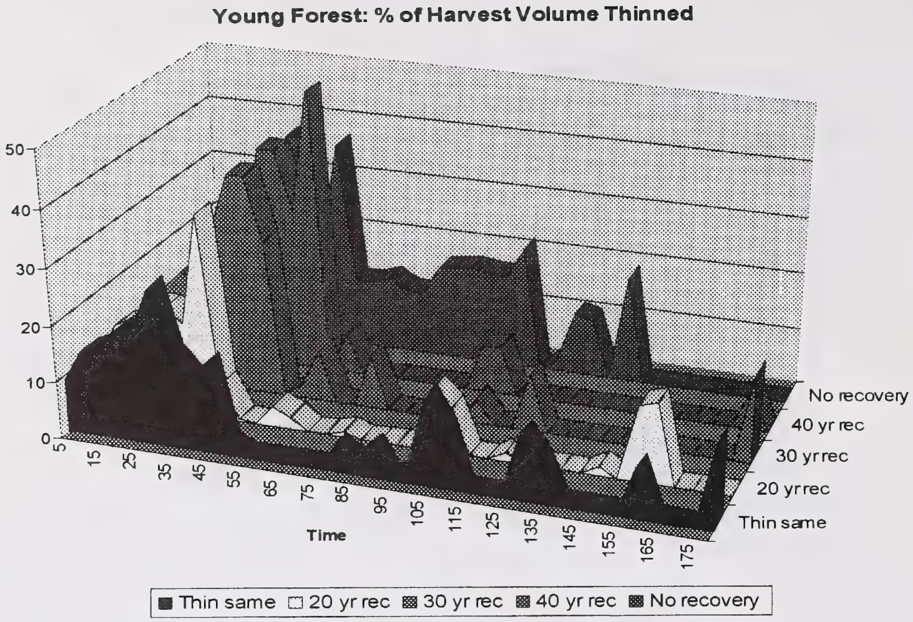

Figure 15. Percentage of harvest volumes from thinning in the Young Forest under the Normal Constraints Strategy.

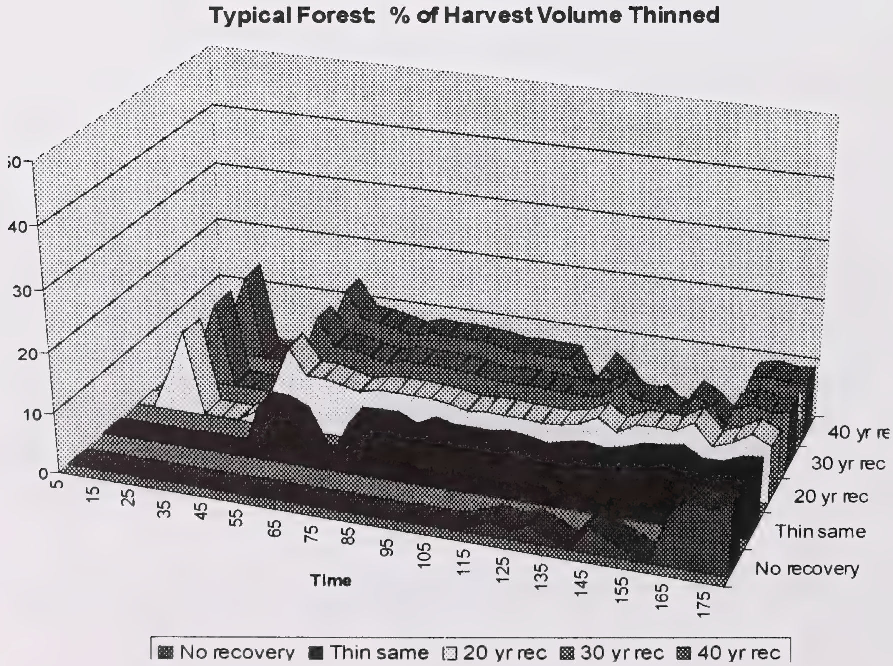

Figure 16. Percentage of harvest volumes from thinning in the Typical Forest under the Normal Constraints Strategy.

Evaluating Stand Density Management Alternatives Using the Forest Vegetation Simulator

Gary Dixon[1]

Abstract

The Forest Vegetation Simulator (FVS) is a software tool available to forest managers to evaluate stand density management alternatives. FVS is widely used in the United States for this and other purposes. Use of FVS in Canada is limited because metric based variants calibrated to Canadian forest types are generally unavailable. FVS is a versatile and powerful tool, capable of simulating almost any management scenario and allowing users to create custom variables and relationships. In addition, model features allow easy calibration of the growth functions to input data. The suite of available FVS software make it an attractive choice to aid forest managers faced with making difficult land management decisions.

Introduction

Forest managers are under ever increasing pressure to design and implement stand management alternatives which are biologically and economically sound. Costs associated with timber harvesting are continually increasing which requires that any stand entry generate enough revenue to justify the treatment. The generated revenue must cover the direct cost of the harvest and also the interest which could have been generated by using those monies in other investment alternatives. Generated revenue can be in the form of direct return on the timber harvested, or in delayed return from increased future revenue as a result of increased tree growth resulting from an intermediate treatment. Meanwhile, forest managers must maintain or improve the health, condition, and scenic value of the landscape to satisfy various forest practices legislation. Traditional forest management practices such as clearcutting are often not acceptable. Forest Managers are faced with implementing management alternatives of which the long-term effects on the resource are unknown.

However, forest managers have available to them an ever increasing array of tools which can aid resource management decisions. Computer technology has revolutionized land management decision analyses. Geographic information systems, relational data bases, mapping technologies, visualization software, and growth and yield simulators are among the many tools currently available, and other software products are being rapidly developed. The Forest Vegetation Simulator is one of the products currently available to aid forest managers in making sound biological and economical management decisions.

What Is The Forest Vegetation Simulator?

Who Uses It and For What Purposes

The Forest Vegetation Simulator (FVS) is a growth and yield simulator which is used extensively in the United States. FVS is the standard growth and yield model used in various government agencies including the USDA Forest Service, USDI Bureau of Land Management, and USDI Bureau of Indian Affairs. It is also used by state agencies such as the Washington Department of Natural Resources, industry, educational institutions, and private land owners. Versions of FVS are currently under development for parts of British Columbia, Canada, and the southern United States.

Forest managers have used FVS extensively to summarize current stand conditions, predict future stand conditions under various management alternatives, and update inventory statistics. Output from the model is used as input to forest planning models such as SPECTRUM (USDA 1996). Uses of FVS are not restricted to timber management applications. Other uses of FVS include considering how management practices affect understory composition, determining suitability of a stand for wildlife habitat, estimating hazard ratings, and predicting losses from fire and insect outbreaks.

Products and Support

Versions of the model which have been calibrated to a certain geographic areas are called "variants." There are currently twenty geographic variants of FVS in use in the United States (Figure 1), with two others currently under development, and more planned for future development. FVS in the United States is supported and maintained by the USDA Forest Service, Forest Management Service Center (FMSC), in Fort Collins, Colorado, with technical assistance from Project 4155 at the Rocky

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Mountain Forest and Range Experiment Station's Laboratory in Moscow, Idaho. FMSC staff distribute the computer software, provide hot-line user support, develop new variants, debug the code, incorporate new enhancements, provide FVS training, and sponsor FVS user conferences.

The suite of FVS software available includes various preprocessors which screen inventory data and translate it into FVS format; twenty FVS variants calibrated to specific geographic areas, various post-processors which further analyze and summarize FVS output files, and stand visualization software. Each of these software products are stand-alone programs integrated via a Graphical User Interface, called Suppose (Crookston, 1998), which allows users to run the model in a Windows type point-and-click format. With the Suppose interface, users can easily make multiple stand runs, create custom output files, and develop and edit FVS input files. The remainder of this paper will focus only on the growth and yield simulator.

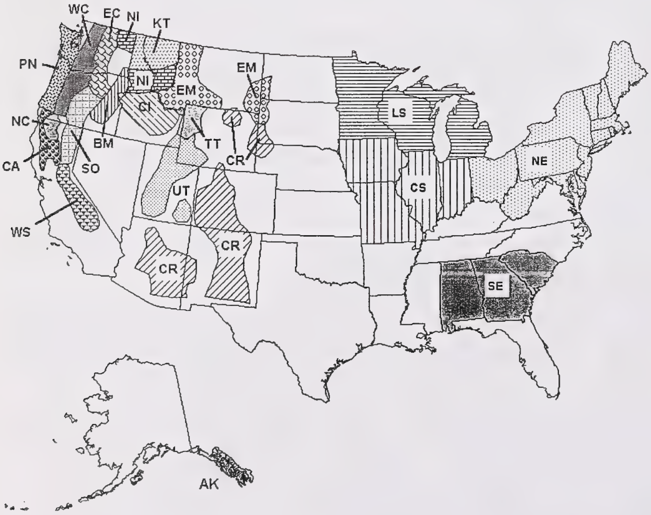

Figure 1: Distribution of FVS variants in the United States.

FVS Basic Description

FVS is a distant-independent individual tree growth and yield model. It treats a stand as the population unit and utilizes standard forest inventory or stand exam data. Local growth rates are used to adjust model growth relationships, which is a distinguishing feature of the model. FVS can portray a wide variety of forest types and stand structures ranging from even-aged to uneven-aged, and single to mixed species in single to multi-story canopies. FVS was originally called The Prognosis Model for Stand Development (Stage 1973; Wykoff, Crookston, Stage 1982; Wykoff 1986, Wykoff, Dixon, Crookston et al 1990) and developed for use in the Inland Empire area of Idaho and Montana. Extensions to the base model have been developed to dynamically schedule activities and compute custom output variables (Crookston 1990), provide for multi-stand simulations (Crookston and Stage 1991), simulate regeneration (Ferguson and Crookston 1984, Ferguson and Crookston 1991), estimate canopy and shrub biomass (Moeur 1985), estimate impacts from various insects and pathogens (Marsden, Eav and Thompson 1993; Stage, Shaw, et al 1990; Monserud and Crookston 1982; Hawksworth, Williams-Cipriani, et al 1992; Crookston, Colbert, et al 1989; Cole and McGregor 1983), and simulate forest fire effects.

Two input files are generally used when running FVS. The first, a keyword file, is required; the second, a tree data file, is required when simulating an existing stand but not required when making a bare ground projection. Keyword records are used to enter stand level parameters such as slope, aspect, elevation, information about the sampling design, location, and site productivity. They are also used to describe management scenarios, control the printing of output, compute custom variables, and adjust model estimates. Keyword records are mnemonic words (keywords) associated with up to seven parameters which provide data necessary and specific to the keyword action. The tree data file is composed of records containing tree level information. Species and diameter at breast height are required on each tree record, and optional data includes tree count, diameter growth, height, height growth, crown ratio, and various other tree level information typically collected in inventory or stand exam procedures.

Four output files are generally produced from FVS. The main output file contains information about keyword interpretation and scheduled activities, shows information about model calibration to the input data, provides stand composition statistics through time, tracks individual sample trees through time, produces a stand summary table of the entire simulation, and a summary of the management activities that were simulated. The treelist output file contains detailed information about all the individual tree records being projected. This file is optional and must be requested via a keyword. The third output file contains only the summary table information from the main output file. This file is useful when summarizing information about many stands or providing information to various planning models. The fourth output file contains information needed when running the economics model linked to FVS (Horn, Medema, Schuster 1986) and can be used for other auxiliary output data such as detailed calibration data needed for a post-processor program to develop model multipliers over a broad geographic scale.

The length of time over which simulation results are desired is specified in terms of "cycles." A cycle is a period of time for which increments of tree characteristics are predicted. The default cycle length is 10 years for most variants and the default number of cycles is 1. However, the cycle length and number of cycles is easily adjusted using appropriate keywords. Thinnings are assumed to take place at the beginning of the cycle in which they are scheduled. Consequently, growth projections for a cycle are done using residual stand conditions. Mortality occurs at the end of a cycle, and new tree records generated from regeneration and plantings during a cycle are added into FVS at the end of the cycle. The general model flow is shown in Figure 2.

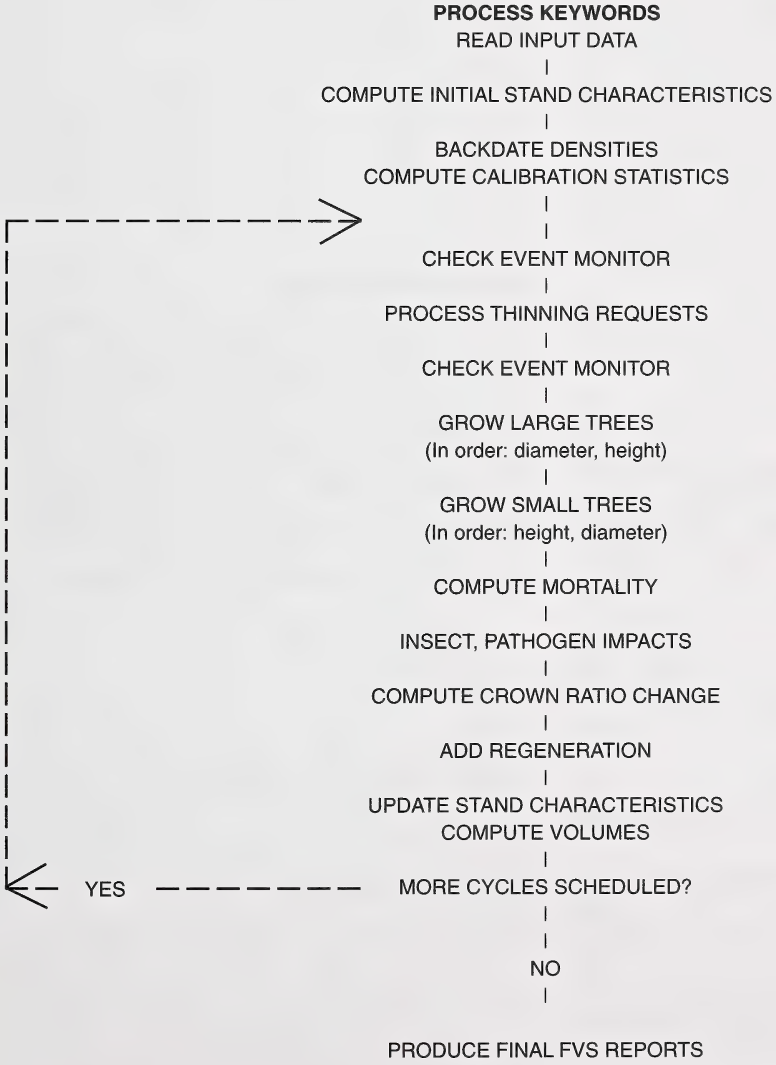
PROCESS KEYWORDS
READ INPUT DATA
COMPUTE INITIAL STAND CHARACTERISTICS
BACKDATE DENSITIES
COMPUTE CALIBRATION STATISTICS
CHECK EVENT MONITOR
PROCESS THINNING REQUESTS
CHECK EVENT MONITOR
GROW LARGE TREES
(In order: diameter, height)
GROW SMALL TREES
(In order: height, diameter)
COMPUTE MORTALITY
INSECT, PATHOGEN IMPACTS
COMPUTE CROWN RATIO CHANGE
ADD REGENERATION
UPDATE STAND CHARACTERISTICS
COMPUTE VOLUMES
YES
MORE CYCLES SCHEDULED?
NO
PRODUCE FINAL FVS REPORTS

Figure 2. General FVS Processing Sequence

Modelling Stand Density Management Alternatives

Many stand management alternatives can be simulated using FVS keywords. Alternatives can be very simple and explicitly stated where the user specifies in what year a certain activity is to take place. Alternatives can also be very complex where the model monitors user specified parameters and dynamically schedules the activities based on values of the parameters. These concepts will be illustrated in following examples.

Several thinning keywords are available and can be used individually, or in combinations, to produce the desired management action. Thinning can be from below, above, or throughout selected portions of a stand. Thinnings can be to a residual basal area or trees per acre target, where the target is contained in a specified diameter and/or height segment of the population. Stand level targets can also be specified if desired. Residual targets can be specifically set by the user, or dynamically calculated by the model using user specified equations. Prescription thinnings are permitted which can target individual trees, and automatic thinnings can be scheduled to maintain a stand within a specified density management zone. Also, certain tree attributes, such as dwarf mistletoe rating or tree value class, can be either favored or discriminated against in a thinning.

FVS Thinning Methodology

The method by which FVS simulates a harvest is very simple. Each tree record within FVS has a tree count attribute which indicates the number of trees per acre the tree record represents. If the other tree attributes (diameter, height, etc.) fall within the harvest parameters, then the tree count attribute is simply reduced to reflect how many of the trees per acre represented by this tree record are removed. It is possible to remove the entire trees per acre representation , or only a portion of the trees per acre representation, for a tree record during a harvest.

Thinnings can be constrained by specifying standards for minimum acceptable harvests. These constraints can be expressed in volume per acre (merchantable cubic feet or board feet) or basal area (square feet) per acre. Minimum harvest constraints can be changed over time if desired. When minimum harvest constraints are specified, the accumulated removals across *all* thinnings in a cycle must exceed the standards for *all* of the minimum harvest constraints for the cycle, or *none* of the thinnings in that cycle will be implemented.

All thinnings are scheduled by date or cycle, and the date or cycle must fall within the bounds of the simulation. Thinning dates do not need to coincide with the beginning of a cycle, but as stated previously, the thinning will occur at the beginning of the cycle in which it is requested. Any number of thinnings may be scheduled during any one projection cycle. These will be simulated in order of date. Thinnings specified for the same date will be simulated in the order they occur in the input file.

The proportion of trees/acre represented by a tree record that is to be removed in any thinning is referred to as the cutting efficiency. The default cutting efficiency is 1.0 which means all the trees represented by a tree record will be removed. However, the cutting efficiency, which must range between 0.01 and 1.0, can be easily changed using the keywords. Cutting efficiency can be changed for individual thinnings using the cutting efficiency parameter on the thinning keywords, or can be changed globally using another keyword. In some cases, where residual targets are specified, the model dynamically calculates the cutting efficiency necessary to achieve the target.

Prescription Thinning

Prescription thinning is designed to allow users to mark individual trees for removal. One attribute associated with each tree record in FVS is a marking code. Marking codes are specified in the input data and values can range from 0 to 9. Prescription thinnings are requested using the THINPRSC keyword. Keyword parameters are (in order): (1) the date the thinning is requested, (2) cutting efficiency associated with the thinning, and (3) the marking code to be removed in the thinning. For example, the keyword sequence:

```
THINPRSC     1998.   1.0    3
THINPRSC     2008.   0.5    5
```

would remove the entire trees per acre representation of all tree records with a marking code of 3 in the year 1998, and would remove 50% of the trees per acre representation of all tree records with a marking code of 5 in the year 2008.

Size Limit Thinnings

Two thinning keywords allow for removing a portion of a given species diameter or height distribution in a stand, without regard to any other tree attributes. This allows for simulation of treatments such as stand cleaning and overstory removal. Size limits can be specified in terms of diameter at breast height or total tree height. The diameter limit thinning is requested with the THINDBH keyword and the height limit thinning by the THINHT keyword. Each of these keywords have seven parameter fields to specify (in order):

(1) the date the thinning is scheduled,
(2) smallest diameter (or height) to be removed,
(3) largest diameter (or height) to be removed,
(4) cutting efficiency for this thinning,
(5) species code to be removed,
(6) target trees per acre to be left in the previously specified diameter (or height) class,
(7) the target basal area to be left in the previously specified diameter (or height) class.

If both a basal area and a trees per acre target are specified on the same keyword, the trees per acre target is used. However, neither target needs to be specified.

Consider, for example, the keyword sequence:

```
THINDBH  1998.   5   20.   1.  ALL   70.    0.
THINDBH  1998.  20   99.   1.   DF    0.   10.
THINDBH  1998.   0    5.   .5
```

In 1998, the first THINDBH would leave 70 trees per acre of whatever species is in the stand which are 5 inches dbh or greater, up to 20 inches dbh. The "ALL" appearing as the fourth parameter tells the model to harvest all species. The second THINDBH would remove only Douglas-fir 20 inches dbh and larger, leaving 10 square feet of basal area in Douglas-fir with dbh greater than or equal to 20 inches. Species other than Douglas-fir which are 20 inches dbh or greater would not be affected. In each of these instances, since residual targets are specified, the model ignores the specified cutting efficiency of 1.0 and calculates the cutting efficiency it needs to achieve the desired targets while spreading the harvest across the entire specified diameter class. The third THINDBH accounts for logging damage to understory trees and tells the model to remove 50 percent of all the trees less than 5 inches dbh.

Thinnings Aimed Specifically at Controlling Stand Density

The remaining thinning options allow managing stand density while giving consideration to tree size, species, value class, mistletoe rating, and user defined special status codes. In the prescription thinning, all tree records with a specified marking code are eligible for harvest; in the size limit thinnings, all tree records in the defined size class of the specified species are eligible for harvest. In each of these cases, there is no need for establishing a thinning priority for the tree records; ***all*** the tree records meeting the criteria are affected. However, in the remaining thinning options, the forest manager is given the choice of which trees will be favored for harvesting depending on several tree attributes. As a result, each tree record must be assigned a "removal priority" which will determine the order in which tree records are considered for harvesting.

The thinning priority for each tree record is computed as follows:

Priority = (DBH * MD) + SP + (TVC * MT) + (DMR * MM) + (STS * MS)

where: DBH = Diameter at breast height
MD = -1 if thinning from below, 1 if thinning from above
SP = User specified species priority (default 0)
TVC = Tree value class
MT = User specified tree value class multiplier (default 0)
DMR = Tree dwarf mistletoe rating (Hawksworth 0-6)
MM = User specified dwarf mistletoe multiplier (default 0)
STS = Special tree status (specified on the tree record during data input)
MS = User specified special tree status multiplier (default 0)

The probability a tree will be removed in a thinning is proportional to its thinning priority. The tree with the largest priority is removed first; thereafter, trees are selected for removal in descending order of priority until the residual stand density objective is achieved. By manipulating the values of the preference terms (SP, MT, MM, MS) and choosing an appropriate density control option, a thinning strategy can be designed to achieve almost any silvicultural objective. Values of the preference multipliers are specified using the SPECPREF, MISTPREF, and TCONDMLT keywords, and can be changed for every thinning request if desired. Once the preference modifers are set for a simulation, they remain in effect until replaced with new SPECPREF, MISTPREF, or TCONDMLT values.

Thinning to a Basal Area or Trees Per Acre Target

Keywords are available for thinning to a basal area target from above (THINABA) or below (THINBBA), or to a trees per acre target from above (THINATA) or below (THINBTA). Each of these keywords have seven parameters:

(1) date the thinning is scheduled,
(2) residual basal area or trees per acre target in the specified diameter and/or height range,

(3) cutting efficiency,
(4) smallest diameter to be considered for removal,
(5) largest diameter to be considered for removal,
(6) shortest tree to be considered for removal,
(7) tallest tree to be considered for removal.

FVS does not dynamically adjust the cutting efficiency for thinnings specified with these keywords, and each tree record is considered for thinning only once per thinning request. As a result, if the cutting efficiency is set too low, the model may not be able to attain the residual target specified on the thinning request. In this case, the thinning request will be completed, but the residual stand condition will be greater than the target the user had intended. If the initial stand condition is already less than the target specified, the thinning will be cancelled. Users should look at the "Activity Summary" portion of the output to see which thinning requests were simulated, which ones (if any) were cancelled, and which ones were done but the effect was not what they intended.

Automatic Stand Density Control

The last thinning option allows forest managers to automatically maintain stand density within a specified range of normal stocking as determined by maximum stand density index. This keyword (THINAUTO) has four parameter fields specifying (in order):

(1) date that automatic stocking control is scheduled to begin,
(2) percentage of normal stocking that defines the lower limit for stand density,
(3) percentage of normal stocking that defines the upper limit for stand density,
(4) cutting efficiency specific to the automatic thinning request.

FVS keeps track of the current stand density index for a stand, and the maximum stand density index for a stand. With this keyword, a thinning is automatically scheduled from below when the current stand density exceeds the upper level management threshold. The thinning reduces stand density to the lower level management threshold. For example, assuming the stand density index maximum is 500, consider the keyword:

```
THINAUTO      2000.    45.    70.     1.
```

This keyword would result in a thinning any time, beginning in the year 2000, that the current stand density index exceeded 350 (70% of 500) and the stand would be thinned to a stand density index of 225 (45% of 500).

There are three things users should be aware of when using this keyword. First, these management zones are variant specific since default stand density index maximums are variant and species specific. Stand density index maximums can be set, however, using the SDIMAX keyword. Second, this keyword can create management scenarios which are impractical to implement on the ground. Forest managers may not be able to afford to make the multiple entries simulated by this keyword, and the resulting volumes may not cover the cost of the thinning. And third, other alternatives (sets of keywords) can be created to achieve automatic stand density control using the other thinning options, and those alternatives do not have the deficiencies associated with this keyword.

Dynamically Scheduling Thinning Requests

In the examples so far, thinning requests have been scheduled by specifying a date in the first field of the keyword. However, stand management alternatives, and the timing of those alternatives, are often contingent upon several factors. Thinning may be needed if a stand gets too dense, or spraying may be required if an insect outbreak occurs, but how does the forest manager foretell when those events might occur?

The event monitor feature of FVS allows the forest manager to specify a set of conditions that must occur, or thresholds that must be reached, for some management action to be scheduled. The model will monitor those conditions and thresholds and dynamically schedule the management action when the condition and/or threshold is reached. For example, suppose the forest manager wants to harvest 50% of all trees if the stand basal area exceeds 150 square feet. The keyword sequence to simulate this management alternative is:

```
IF
    BBA GT 150
THEN
    THINDBH        0.       0.       999.     0.5
ENDIF
```

The variable BBA represents the before thinning basal area and is one of many event monitor pre-defined variables which can be used to trigger an activity. When contained in an event monitor sequence, the date field on the management action keyword (in this example the first field of THINDBH) is a "waiting time." This tells FVS to schedule the management action a certain number of years after the condition is found true. In this example, the waiting time is 0 so the thinning is scheduled immediately. The second and third parameters define the diameter range 0 - 999 inches (all trees), the fourth parameter sets the cutting efficiency at .5 or 50%, the fifth through seventh parameter fields are blank so default values are used. The default value for the fifth parameter is all species, and default values for the remaining fields are 0 which says there is no basal area or trees per acre target associated with this thinning request.

Pre-defined variables exist for a suite of before-thinning and after-thinning stand values. The event monitor is called twice during a projection cycle; once before thinning to schedule any activities dependent on before-thinning stand values, and once after thinning to schedule any activities dependent on after-thinning stand values. For example, a user may want to plant seedlings following a thinning if the stand density is reduced beyond a certain level. Any FVS management activity that contains a date field can be scheduled by the event monitor. Multiple conditions and multiple management actions can be specified in the same event monitor sequence.

As a second example of this concept, suppose the management alternative is: if before-thinning crown competition factor is greater than 150, and before-thinning trees per acre is greater than 500, and stand age is greater than 20 but less than 60, then thin from below to a residual stand density of 300 trees per acre and 30 years later clearcut the stand. One keyword sequence to simulate this management alternative is:

```
IF
   BCCF GT 150 AND BTPA GT 500 AND &
   AGE GT 20 AND AGE LT 60
THEN
   THINBTA          0.    300.
   THINDBH   30.    0.    999.   1.    ALL    0.    0.
ENDIF
```

The variables BCCF, BTPA, and AGE are pre-defined variables corresponding to the stand values to be monitored. The "0" in the first field of the THINBTA tells FVS to schedule the thin from below immediately, and the "30" in the first field of the THINDBH tells FVS to schedule the clearcut 30 years later. All the keyword parameters have default values. In this example, default values for the last five parameters of the THINBTA keyword are being used. The default values being used are: cutting efficiency of 1.0, smallest dbh of 0 inches, largest dbh of 999 inches, shortest tree of 0 feet, tallest tree of 999 feet—in other words, cut all trees from below until the target is reached.

Creating And Using Custom Variables

In the previous section, the examples used pre-defined variables in the condition statement. Another feature of the event monitor in FVS allows the forest manager to create custom variables which can be used in condition statements, as parameter fields on the keywords, or to report additional output values which are not contained in the standard FVS output. The following example illustrates how custom variables can be created and used.

Assume the forest manager wants to define normal stocking using the equation:

$$\text{normal stocking} = 25000 * (\text{quadratic mean diameter} + 1)^{-1.588}$$

and the intensive management alternative is: once the stand exceeds normal stocking, then thin the stand to the normal stocking level; recheck the stand at 3 year intervals and thin as necessary such that the normal stocking curve is followed; however insure that there is at least five years between entries.

One keyword sequence that would accomplish this alternative is:

```
reference  keyword
line
   (1)     TIMEINT                       0.       3.
   (2)     COMPUTE                       0.
   (3)        NORMAL = 25000 * (BADBH+1)**(-1.588)
   (4)        CURRENT = BTPA
   (5)        RATIO = NORMAL / CURRENT
   (6)     END

   (7)     IF                            5
   (8)        RATIO LT 1.
   (9)     THEN
   (10)       THINDBH       0.           PARMS(0.,999.,1
              RATIO,ALL,0.,0.)
   (11)    ENDIF
```

Line 1: Since the stand needs to be monitored at 3 year intervals, set the time interval for all cycles to 3 years.

Lines 2 to 6: Define the variables NORMAL to be the trees per acre considered normal stocking, CURRENT to be the current trees per acre in the stand, and RATIO to be the ratio between normal stocking and current stocking. In this formulation, when RATIO exceeds 1 then the stand is below normal stocking and if it is less than 1 then the stand is above normal stocking. The variables BADBH and BTPA are the predefined variable representing before thinning quadratic mean diameter, and before thinning trees per acre, respectively. The "0" as the first parameter on the COMPUTE keyword tells the model to compute values for the three variables, NORMAL, CURRENT, and RATIO, every cycle. The computed values of these variables will appear in the FVS output "Activity Summary" table, and can be displayed in charts and graphs using the Suppose interface.

Lines 7 to 11: If the value of RATIO is less than 1 (overstocked condition) then schedule a thinning. A THINDBH option is being used in this example so the thinning will be spread across all tree records uniformly. The cutting efficiency needed to reduce the stand to the normal stocking level is 1-RATIO, and all species will be cut. The string inside the parenthesis of the PARMS statement are the values for the 2nd to 7th parameters required by the THINDBH keyword. The PARMS statement is useful when entering arithmetic expressions as parameter values for a keyword. The "5" appearing as the first parameter on the IF keyword tells the model that once the condition of the if statement is found "true," then don't consider making this test for another 5 years.

FVS Power and Versatility

The above examples illustrate how management scenarios might evolve as a forest manager first tries to use FVS and then becomes increasingly more knowledgeable about its capabilities. Hopefully they also stimulate the imagination about what might be possible once a user becomes proficient with all the capabilities of the model. FVS is extremely powerful and versatile. Approximately 150 keywords, only a few of which are illustrated here, are available to control the base model with regeneration and mistletoe modules included. Other keywords are available to control additional FVS extensions such as those for insect and pathogen outbreaks and effects, multistand processing for landscape simulations, and fire effects.

The way the FVS keyword system is designed borders on a programming language all its own. Extremely complex management scenarios can be simulated for wildlife or other purposes. Users taking advantage of the ability to create custom variables, define mathematical relationships, and conditionally schedule events, have created "models" of their own using the FVS model. Keyword sets hundreds of lines long achieve mind-boggling results never dreamed of when the FVS system was first developed. Highly creative minds push the limits of the model to further extremes on a daily basis. New capabilities are added continually, by the development staff, in response to the never ending user request "Can you make the model do...?" And yet with all the power, versatility, and capabilities, FVS remains a relatively easy model to use for the forest manager who only occasionally needs simple projections and is content with a basic knowledge of how the model operates.

How Can FVS Be Used In Canada

Three possibilities currently exist for using FVS in Canada: (1) use one of the FVS variants being developed for British Columbia, (2) develop new variants for Alberta and other Canadian Provinces, (3) use currently existing US variants to simulate Canadian stands. The first alternative may be the most promising in terms of implementing FVS in the shortest time frame with the least complications. The BC variants will be based on metric units which is an advantage over trying to use the US variants. It takes about a year to develop and test a new variant. So the second alternative, while clearly being the best solution, is not timely. The third alternative could be implemented in the least amount of time if the problem with measurement units could be overcome. In any case, the first and third alternatives should be viewed as short term solutions for a given geographic area, and the second alternative as the long term solution. The remainder of this paper examines the third alternative.

Self Calibration to the Input Data

FVS will automatically calibrate its growth equations, by species, to match the input data unless this feature is "turned off" by user keywords or insufficient observations exist in the input data to calibrate the specific equation. To understand this feature, a basic understanding of FVS structure is necessary.

FVS growth relationships are broken into two categories; those for "small" trees, and those for "large" trees. In most variants the diameter break between a small and large designation is 3.0 inches dbh. The small tree growth relationships are height driven. Height growth is estimated first, then diameter growth is estimated from height growth. The large tree growth relationships are diameter driven. Diameter growth is estimated first, then height growth from diameter growth and other tree and stand variables. Around the 3.0 inch break point (or the appropriate break between the large and small tree relationships), growth estimates from the small and large tree equations are blended to assure a smooth transition between the two sets of relationships.

FVS is a forward predicting model. To calibrate the growth relationships, FVS "backdates" the stand by subtracting growth measurements, adding in recent mortality, growing the stand forward to the current inventory year, comparing the estimated tree attributes with the actual tree attributes at the inventory year, and computing adjustment factors based on the difference of actual and estimated values. Equations which are calibrated are: (1) large tree diameter growth, (2) small tree height growth, (3) height-diameter relationships, and in some variants (4) the maximum stand density index. The large tree diameter growth equation for a species is adjusted if 5 diameter increments exist in the input data on trees whose backdated dbh is larger than 3.0 inches. The small tree height growth equation for a species is adjusted if 5 height increments exist in the input data on trees whose diameter is less than 5.0 inches. Height-diameter relationships are adjusted for any species which has 3 or more heights measured on trees which are 3.0" dbh or greater. The maximum stand density index is adjusted if the initial stand density index exceeds 90% of the initial maximum stand density index.

The self-calibration feature of FVS extends the geographic range over which the model can be used, assuming that the same factors which affect growth in one area also affect growth in the same relative way in another area. If this assumption cannot be accepted, the only other option is to refit the relationships using data from the geographic area of interest. If this assumption can be accepted, then the model equations can be calibrated rather easily.

The diameter and height growth adjustment factors, called scale factors, are attenuated over time. The attenuation is asymptotic to one-half the difference between the initial value of the scale factor and 1. However, if there is a consistent bias in the scale factors for any species over a representative inventory of stands from a geographic area, the average value of the scale factors for that species can be entered into FVS as an equation multiplier using keywords. Multipliers entered with keywords are not attenuated over time. In effect then, the average scale factor becomes a new estimate of the model intercept, and the user has adjusted the growth equation to the particular geographic area. The suite of available FVS software provides users with a way of collecting and analyzing scale-factors so multipliers, if needed, can be easily determined.

Summary

The Forest Vegetation Simulator is a versatile and powerful software tool available to forest managers. The model can be used to evaluate stand density management alternatives, but its potential for aiding land management decisions extends far beyond that single application. The suite of FVS software available, including the GUI interface, the model itself, visualization software, many auxiliary output processing programs, links to forest planning models, and so forth, make it an attractive choice to aid forest managers faced with making difficult land management decisions. Since the FVS growth equations can be readily calibrated to the input data, the geographic range of a particular FVS variant can be extended beyond the data which was used to develop the equations.

Although FVS is the growth and yield model endorsed and supported nationally in the United States, making it available to Canadian forest managers will require a significant effort. Development of FVS variants is underway for British Columbia, but these variants are years away from being readily available. Other Canadian Provinces are only beginning to hear about FVS and what it can do. Furthermore, use of existing United States variants by Canadian forest managers is hampered by the difference in measurement systems.

A concerted effort is needed to make FVS technology generally available in Canada. An initial step in this direction is a Memorandum Of Understanding which currently exists between the British Columbia Ministry of Forests and the United States Forest Service. This agreement provides for cooperation and communication between FVS specialists in the US and BC. It also provides for sharing experience and expertise relating to all facets of the FVS system. With efforts like these, FVS may soon become a reality for forest managers in the Canadian Provinces.

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